I. Introduction

The transcutaneous energy transmission system (TETS) composed of a Class-E amplifier may operate at a state away from the optimum power transmission due to the load variation. By introducing the feedback-loop technique, the TETS can keep the optimum state with constant output voltage by adjusting the important design parameters, that is, the duty ratio and frequency of the driving signal and the supply voltage. The relations between these adjusted parameters and the load are investigated. The effectiveness of the feedback technique is validated through a design example with a variable load parameter. The experimental results show that the Class-E amplifier in the feedback loop can keep operating at the optimum state under the condition of up to 50 percent variation of the load value.

Keywords: Transcutaneous energy transmission system (TETS), Class-E amplifier, feedback systems, efficiency.
design example was constructed to validate the expressions.

II. Circuit Description

A schematic diagram of the simplified model of a typical TETS is shown in Fig. 1. This model consists of a primary circuit with a Class-E power amplifier, a secondary circuit with a resonant circuit and a rectifier, and a pair of inductive coils by which the transcutaneous energy can be transmitted from the primary circuit to the secondary one [3]. The Class-E amplifier consists of a choke coil $L_f$, a switch $S$, a shunt capacitance $C$, and series resonant circuit comprised of a capacitance $C_1$ and a transmitter coil $L_1$. The resonant circuit consists of a receiver coil $L_2$ and a resonant capacitance $C_2$. The rectifier consists of a rectifier diode $D_r$ and filter capacitance $C_r$. $R_L$ is the load parameter.

The secondary circuit contains a diode, thus making this circuit nonlinear. To facilitate derivation of analytical parameter equation for each component, the secondary circuit is converted to a linear model by transferring the DC load to an AC equivalent linear load. The inductive coils link the primary circuit and the secondary circuit, and the impedance of the secondary circuit can be reflected into the primary one [11] as

$$ Z_{el} = \frac{\omega_0^4 M^2}{Z_2} $$

$$ = \frac{\omega_0^4 k^2 L_1 L_2 (4 + \omega_0^2 C_1^2 R_2)}{4 R_1^2 + \left[ \omega_0 L_2 (4 + \omega_0^2 C_1^2 R_2^2) - \omega_0 C_1 R_1 \right]} $$

$$ \times \left[ 2 R_1 - f \left[ \omega_0 L_2 (4 + \omega_0^2 C_1^2 R_2) - \omega_0 C_1 R_1 \right] \right] $$

$$ = R_{el} + jX_{el}, $$

where $\omega_0$ is the operating frequency, $M$ is the mutual inductance of the primary coil $L_1$ and secondary coil $L_2$ with $M^2 = k^2 L_1 L_2$, $k$ is the coupling coefficient, $Z_2$ is the impedance of the secondary circuit looking into the receiver from the mutual inductance, and $R_{el}$ and $X_{el}$ are the real and imaginary parts of $Z_{el}$, respectively.

With the reflected impedance $Z_{el}$, the primary circuit can be redrawn as a basic Class-E amplifier as shown in Fig. 2. $v_g$, with the duty ratio $D$ and angular frequency $\omega_0$, is the driving signal for the Class-E amplifier.

III. Component Determination at Any Duty Ratio

When the TETS load $R_L$ changes, the reflected impedance $Z_{el}$ will change. The Class-E amplifier in the primary circuit may lose its optimum state, and the output voltage may also change. The duty ration $D$ and angular frequency $\omega_0$ of the driving signal $v_g$ require adjustment to make the TETS return to the optimum state: the supply voltage needs to be adjusted to keep the output voltage constant. In order to derive $D$ and $\omega_0$ as functions of $R_L$, the component parameter are obtained as functions of $D$ and $\omega_0$ by frequency domain analysis of the steady-state switch voltage $v_s$ and output current of the Class-E amplifier $i_{o1}$. This happens under the assumptions that the choke coil is large enough and the load quality factor is high enough.

According to the assumption of the high load quality factor, the sinusoid output current of the Class-E amplifier $i_{o1}$ can be expressed as

$$ i_{o1} (\theta) = I_{o10} \sin \theta, $$

where $I_{o10}$ is the current amplitude and $\theta = \omega_0 t$ is the phase angle. Considering the large choke coil, the input current $I_{DD}$ is approximate to direct current.

For the zero-voltage switching (ZVS) condition and zero-derivative switching (ZDS) condition [7], [8], [10], the output current $i_{o1}$ equals the supply current $I_{DD}$ at the instant when the switch turns on, as shown in Fig. 3. The relationship between
\( I_{\text{DD}} \) and \( i_{\text{c}} \) can be expressed as
\[
I_{\text{DD}} = I_{\text{olen}} \sin \theta_X,
\]
where \( \theta_X = \pi - \theta_{\text{PD}} \), \( \theta_{\text{PD}} \) is the phase angle difference between \( i_{\text{c}} \) and \( v_s \).

For the ZVS condition [7], [8], [10], the charge quantity of the shunt capacitance \( C \) is zero. Hence, the combination \( v_s \) can be expressed in the frequency domain as
\[
V_s(j\omega) = I_c(j\omega)\omega C,
\]
where \( I_c(j\omega) \) is the Fourier transform function of \( i_c \). In the switch off duration, \( i_c = I_{\text{DD}} - i_{\text{c}} \). In the switch on duration, \( i_c = 0 \). \( i_c \) can be expressed in the frequency domain as
\[
I_c(j\omega) = \frac{2}{\pi} \sum_{p=0}^{\infty} \left[ \frac{\sin \theta_X}{p} \frac{2 \sin p \theta_c}{2} e^{-p \omega_l} + \frac{2 \sin (p+1) \theta_c}{p+1} e^{-[(p+1)\omega_l] \frac{z}{2}} + \frac{2 \sin (p-1) \theta_c}{p-1} e^{-[(p-1)\omega_l] \frac{z}{2}} \right] \delta(\omega - p\omega_c).
\]

Since the choke coil is large enough, the input current is direct, and the voltage drop of the choke coil is zero. Hence, the supply voltage \( V_{\text{DD}} \) equals the DC voltage component of \( V_s \), writing:
\[
V_{\text{DD}} = V_s(0) = \frac{I_{\text{olen}}}{2\pi\omega_c C} \alpha,
\]
where \( \alpha = -\theta_s \theta_c \sin \theta_X + \theta_c \cos \frac{\theta_c}{2} \cos \theta_c + 2 \sin \frac{\theta_c}{2} \cos \theta_c + 2 \theta_s \sin \frac{\theta_s}{2} \sin (\theta_c) \), \( \theta_s = 2\pi - \theta_c \), and \( \theta_c = \theta - \theta_X \).

The load impedance of the Class-E amplifier at \( \omega_0 \) can be expressed as \( Z_{\text{IL}} = R_{\text{el}} + j(X_{\text{el}} + \omega_0 L_{\text{a}} - 1/\omega_0 C_1) \), and it can also be determined by \( Z_{\text{IL}} = V_{\text{s}}(\omega_0) / I_{\text{DD}}(\omega_0) \) in the frequency domain, where \( V_s(\omega_0) \) is the steady-state switch voltage and \( I_{\text{DD}}(\omega_0) \) is the output current. Hence, the real and imaginary parts of \( Z_{\text{IL}} \) can be obtained as
\[
R_{\text{el}} = \frac{1}{2\pi\omega_c C} \beta
\]
and
\[
X_{\text{el}} + \omega_0 L_{\text{a}} - \frac{1}{\omega_0 C_1} = \frac{1}{2\pi\omega_c C} \gamma,
\]
where \( \beta = \left[ \sin \theta_X + \sin \left( \theta_s - \theta_X \right) \right]^2 \) and \( \gamma = \theta_c \cos 2\theta_X + \sin \theta_s \cos 2\theta_c \).

In the TETS, the duty ratio \( D \), the supply voltage \( V_{\text{DD}} \), and the input power \( P_{\text{in}} \) are always design parameters. \( P_{\text{in}} \) equals the input power \( P_{\text{in}} \) if the parasitic resistance of each component is zero. From (3), (7), and (8), \( R_{\text{el}} \) can be expressed by \( P_{\text{in}} \), \( V_{\text{DD}} \), and \( D \) by
\[
R_{\text{el}} = \frac{\beta \sin \theta_X V_{\text{DD}}^2}{\alpha P_{\text{in}}}.
\]

With the calculated \( R_{\text{el}} \), the shunt capacitance \( C \) can be determined by (8). The inductance \( L_1 \) can be obtained by \( L_1 = Q R_{\text{el}} / \omega_0 \) with the given quality factor \( Q \). As \( L_1 \) is required to be a suitable value, it can be determined by \( L_1 = 2(\pi^2/4+1)R_{\text{el}} / f \) [12].

From (1), the resonant capacitance \( C_2 \) is determined under the resonant conditions (\( \omega_0 = 1/\sqrt{L_2 C_2} \)) as
\[
C_2 = \frac{2R_{\text{el}}}{\omega_0^2 k^2 L_1 R_{\text{el}}}.
\]

Then the resonant inductance \( L_2 \) is obtained by the resonant conditions. At last, the capacitance \( C_1 \) can be determined from (9).

If the secondary circuit is adopted as a linear one, the TETS...
Table 1. Design parameters of the TETS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power ($P_{out}$)</td>
<td>1 W</td>
</tr>
<tr>
<td>Supply voltage ($V_{DD}$)</td>
<td>6 V</td>
</tr>
<tr>
<td>Quality factor ($Q$)</td>
<td>10</td>
</tr>
<tr>
<td>Duty ratio ($D$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Operating frequency ($f$)</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Coupling coefficient ($k$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Load resistance ($R_L$)</td>
<td>1 kΩ</td>
</tr>
</tbody>
</table>

Table 2. Component values of the TETS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_f$</td>
<td>400.0 μH</td>
</tr>
<tr>
<td>$C_1$</td>
<td>1.4 nF</td>
</tr>
<tr>
<td>$L_1$</td>
<td>33.0 μH</td>
</tr>
<tr>
<td>$C_1$</td>
<td>907.3 pF</td>
</tr>
<tr>
<td>$L_2$</td>
<td>31.8 μH</td>
</tr>
<tr>
<td>$C_2$</td>
<td>795.8 pF</td>
</tr>
<tr>
<td>$R_{eL}$</td>
<td>20.8 Ω</td>
</tr>
</tbody>
</table>

with the design component parameter will operate in the optimum state. If the secondary circuit is adopted as a nonlinear circuit, it needs additional component parameter adjustments to make the TETS operate in the optimum state. In order to facilitate the feedback analysis, the secondary circuit is considered to be a linear one.

### IV. Design Example

The component parameters are functions of the duty ratio $D$ and the angular frequency $\omega_0$. Conversely, $D$ and $\omega_0$ have relations with component parameters as well as the load parameter $R_L$. In order to derive the variation trends of $D$ and $\omega_0$ with respect to $R_L$, the TETS driven by a Class-E amplifier is analyzed in a design example as follows.

1. **Design Parameters**

The example is designed to operate at the design parameters given in Table 1, and the calculated component values are calculated and shown in Table 2.

2. **Variations of the Load Parameter**

The variation of the load parameter $R_L$ will lead to the detuning of the Class-E amplifier. It is necessary to adjust the duty ratio $D$ and the frequency $\omega_0$ of the driving signal $v_g$ to keep the Class-E amplifier tuning when $R_L$ changes.

Combining (1), (8), and (9), the relationship between $D$ and $\omega_0$ is determined as

$$\frac{L_f^2 C_1^2 R_L}{2} \omega_0^2 - \frac{L_f C}{\alpha} \omega_0^2 + \left( \frac{2 C_1}{R_L} - \frac{C C_1}{2} \right) \omega_0^2 + \frac{C}{\alpha} \beta \omega_0 = 0 .$$

(12)

It is a cubic equation at the given $D$ and $R_L$. Although the equation has three roots, only one effective real root satisfies the design example. Substituting this effective root back into (1) and (8), $D$ and $\omega_0$ with respect to $R_L$ are obtained and shown in Figs. 4 and 5, respectively. The Class-E amplifier can be tuned in two operating regions: operating region 1 and operating region 2. The operating region 1 contains the design $D$ and $\omega_0$, and the $D$ variation range is between 0.4 and 0.7, which is a suitable duty ratio for the Class-E amplifier. However, the duty ratio of the operating region 2 is between 0.1 and 0.2, and it requires a much larger $V_{DD}$ to reach the designated output power, thus, the operating region...
2 is not suitable for an actual application. The output voltage $V_o$ is expected to keep constant when $R_L$ changes. The load $R_L$ changes, and the output power $P_{out}$ will also change. Thus, the input power $P_{in}$ is required to be changed. Ignoring the parasitic resistance of each component, the output power $P_{out}$ equals the input power $P_{in}$ when the TETS operates in the optimum state. From (8) and (10), $V_{DD}$ as a function of $R_L$ is determined and shown in Fig. 6. The supply current $I_{DD}$ and the output current amplitude of the Class-E amplifier $I_{o1m}$ from (2) and (7) can be seen as functions of $R_L$ (Fig. 7). $I_{DD}$ and $I_{o1m}$ decrease when $R_L$ increases.

3. Feedback Control

In order to implement the feedback control, the adjusted parameters need to vary with the load $R_L$ as the designated. The phase difference $\theta_{PD}$, which is between $i_{o1}$ and $v_g$, will vary with the load parameter, and can be employed as the feedback quantity. As shown in Fig. 8, the current transformer (CT) (note that the output voltage of the CT will add 90° of phase shift) detects the phase of the output current $i_{o1}$. The output of the phase comparator is the control voltage $v_F$, which varies with $\theta_{PD}$ in direct ratio. $v_F$ controls the Class-E control unit to output $v_g$, whose duty ratio $D$ and angular frequency $\omega_0$ vary with $R_L$ as shown in Figs. 4 and 5, to keep the class-E operate in the optimum state. $v_F$ controls the supply voltage control unit to keep the output voltage constant.

4. Experiment

In order to experimentally validate the closed-loop model of the inductive power link, the design example was constructed and tested. The secondary circuit was adopted as a linear model. The MOSFET IRF 510 was employed as the switch. The driving signals were derived from a function generator. All capacitors were Silver Mica, and the inductive coils were made of the Litz wire which consists of 200 strands with the diameter of 0.1 mm. The capacitors and the inductors were measured at the intended operating frequency of 1 MHz.

The load parameter was designated to vary ±50% from the nominal load value. The corresponding adjustments of the duty ratio $D$, the angular frequency $\omega_0$, and the supply voltage $V_{DD}$ are shown in Table 3. The wave forms of the switch voltage $v_s$ and the output voltage $v_o$ are shown in Fig. 7. Note that $v_s$ returns to zero smoothly when the switch turns on, and the slopes of $v_s$ are zero at the turn-on time; therefore, the Class-E amplifier operates at the optimum state. The parasitic resistance of each component are actually exists, and the efficiency is different at different load $R_L$ [13]. $V_{DD}$ requires additional adjustment to keep the output voltage constant. $V_{DD}$ was adjusted to 5.1 V, 6.4 V, and 7.0 V when $R_L$ were 500 Ω, 1000 Ω, and 1500 Ω, respectively. The input power $P_{in}$, the output power $P_{out}$ and the efficiency $\eta$ are shown in Table 3. The efficiency is lower when the load is smaller because the equivalent load resistance $R_{eq}$ is smaller, and parasitic resistance affects the power link more. In the low power
Fig. 9. Experiment waveform: (a) \( R_L = 0.5 \, \text{k}\Omega \), (b) \( R_L = 1 \, \text{k}\Omega \), and (c) \( R_L = 1.5 \, \text{k}\Omega \).

Table 3. Adjusted parameters, power, and efficiency.

<table>
<thead>
<tr>
<th>( R_L ) (k\Omega)</th>
<th>( D )</th>
<th>( f ) (MHz)</th>
<th>( V_{DD} ) (V)</th>
<th>( V_o ) (V)</th>
<th>( P_{in} ) (W)</th>
<th>( P_{out} ) (W)</th>
<th>( \eta ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.63</td>
<td>0.95</td>
<td>4.5</td>
<td>31.6</td>
<td>2.35</td>
<td>2.00</td>
<td>85.1</td>
</tr>
<tr>
<td>1.0</td>
<td>0.50</td>
<td>1.00</td>
<td>6.0</td>
<td>31.6</td>
<td>1.11</td>
<td>1.00</td>
<td>90.1</td>
</tr>
<tr>
<td>1.5</td>
<td>0.43</td>
<td>1.07</td>
<td>6.8</td>
<td>31.6</td>
<td>0.70</td>
<td>0.67</td>
<td>95.7</td>
</tr>
</tbody>
</table>

V. Conclusion

The TETS with a Class-E amplifier was analyzed and the design equations were derived at any duty ratio. A design example was adopted to analyze the variation trends of the main electric parameters, such as the duty ratio and frequency of the driving signal and the supply voltage, varied with the load parameters. The duty ratio and frequency of the driving signal were adjusted to keep the TETS operating at the optimum state, and the supply voltage was adjusted to keep the output power constant. The design example with a load variation of \( \pm 50\% \) was constructed to validate the theory model, and the experiment result shows that the power link operated at the optimum state with a constant output voltage.

References

[11] N. de N. Donaldson and T.A. Perkins, “Analysis of Resonant implant system, such as the retinal implants, the cochlear implants, and the functional electrical stimulation applications, the reflected resistance will be large at the same \( D \) and \( V_{DD} \). The effects of component parasitic resistance will be low, and the efficiency will be large.


Tianliang Yang received the BS in electrical engineering and the MS in mechatronics engineering from Nanchang Hangkong University, Nanchang, China, in 2003 and 2006, respectively. Currently he is working toward the PhD in electrical engineering at Shanghai Jiao Tong University. His research interests include power amplifier, DC/DC converters, wireless power and data transfer, implantable electronics, and smart telemetry.

Chunyu Zhao received the PhD from Shanghai Jiao Tong University, Shanghai, China, in 2000. Currently, he is an associate professor of the Department of Instrument Science and Engineering at Shanghai Jiao Tong University. His research interests include prosthetic devices, power amplifier, dc/dc converters and inductive links, neural-electronic interfaces, and wireless biotelemetry.

Dayue Chen received his PhD from Shanghai Jiao Tong University, Shanghai, China, in 1989. Currently, Prof. Chen is the Director of the Institute of Intelligent Mechatronics Research of Shanghai Jiao Tong University. His research interests include prosthetic devices, neural-electronic interfaces, implantable electronics, inductive links, and smart telemetry.