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Transcutaneous Battery Recharging By Volume Conduction and its Circuit Modeling

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Abstract—**Many implantable devices require large capacity batteries implanted in the body. Transcutaneous battery recharging can effectively maintain the longevity of these implants. Based on this consideration we have developed a transcutaneous battery recharging circuit unit which takes advantages of skin volume conduction. This unit is able to pass 2.8 mA from the outside to the inside of pig skin with a current transmitting efficiency of 27%. Theoretical analysis and experiments have validated that this battery recharging technology is an effective approach. In this research we have constructed an x-type equivalent circuit model of skin volume conduction for battery recharging. The parameters of the x-type equivalent circuit can be easily measured and used to evaluate the battery charging system characteristics, such as the rechargeable prerequisite and the current transmitting efficiency limitation. We have analyzed the transcutaneous current transmitting efficiency by applying the x-type equivalent circuit model and discussed approaches for enhancing current transmitting efficiency.**

I. INTRODUCTION

SIGNIFICANT numbers of implantable devices have been designed for various clinical applications, such as cardiac pacemakers, retinal prostheses, implantable drug delivery systems, implantable defibrillators, and functional neuromuscular stimulators [1]. For implantable devices, power supply is a common concern. At present, there are mainly three practical power supply approaches: radio frequency coupling [2], photovoltaic energy conversion [3], and a chemical battery [1]. Because the lithium battery has a high energy density, it is widely used in implantable devices. However, batteries only have limited energy, so they must be recharged to maintain implants' longevity. Based on this consideration, we have devised recharging circuits using human skin volume conduction properties. This paper addresses our research results from the recharging circuits.

II. RECHARGEABLE PRINCIPLE AND CIRCUIT MODEL OF VOLUME CONDUCTION

Our approach to transcutaneous power delivery is to pass electric current through skin using volume conduction properties of the human body. We can transfer energy through the skin to energy-storage elements, such as batteries and supercapacitors, which are implanted in the body. Fig.1 shows a model for energy delivery through volume conduction of skin. The gray layer denotes the skin and the connective tissue. The battery between exterior electrodes 1 and 2 charges the battery between interior electrodes 3 and 4 through the skin and tissue. R_1 and R_2 are the internal resistances of the batteries. There are two possible simultaneous currents in the skin/tissue layer: penetrating and transverse. The penetrating current is the recharging current for the internal battery, while the transverse current consumes energy and may hurt the skin or cause sensory responses. Thus, the transverse current must be minimized. Supplying the largest relative penetrating current possible is the key to recharging the internal battery.

The currents are concentrated on the 4 electrodes, and given a certain frequency, the impedances between electrodes are passive and linear [4]. From points external to the electrodes, the physical model can be viewed as a bulked, passive and linear 2-port network. An equivalent circuit model is shown in Fig. 2. We call it the x-type equivalent circuit. This x-type equivalent circuit model is used here because: (a) it has a physical basis, and the contact impedances between electrodes and skin are parts of circuit impedances Z_b; and (b) the circuit parameters $Z_b=[Z_1,Z_2,Z_3,Z_4,Z_5]'$ are a linear functions of impedances between electrodes. By measuring or theoretically analyzing impedances between electrodes, $Z_{ij}=[Z_{12},Z_{12},Z_{14},Z_{23}, Z_{24},Z_{34}]'$,the circuit parameters, Z_b,can be calculated. From Fig. 2, we have

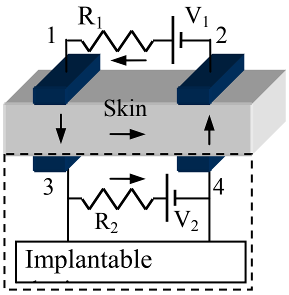

Fig. 1 Phys. model of VC.

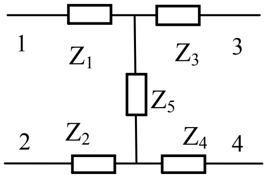

Fig. 2 Equivalent circuit

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$$\begin{bmatrix}1&1&0&0&1\\1&0&1&0&0\\1&0&0&1&1\\0&1&1&0&1\\0&1&0&1&0\\0&0&1&1&1\end{bmatrix}\begin{bmatrix}Z_1\\Z_2\\Z_3\\Z_4\\Z_5\end{bmatrix}=\begin{bmatrix}Z_{12}\\Z_{13}\\Z_{14}\\Z_{23}\\Z_{24}\\Z_{34}\end{bmatrix} \qquad \text{□1□}$$

$$AZ_b = Z_{ij}$$

constrained by

$$Z_{12}+Z_{34}-Z_{14}-Z_{23}=0$$

Where $Z_{n\,m}$ is the impedance between electrodes n and m with the other electrodes being open.

Considering the rank of matrix A which is equal to 5 and the constraint, equation (1) has the unique solution

$$\begin{bmatrix}Z_1\\Z_2\\Z_3\\Z_4\\Z_5\\0\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1&1&0&-1&0&0\\1&0&-1&0&1&0\\-1&1&0&1&0&0\\-1&0&1&0&1&0\\0&-1&1&1&-1&0\\1&0&-1&-1&0&1\end{bmatrix}\begin{bmatrix}Z_{12}\\Z_{13}\\Z_{14}\\Z_{23}\\Z_{24}\\Z_{34}\end{bmatrix} \qquad \text{□2□}$$

III. CONDITIONS FOR RECHARGING BY VOLUME CONDUCTION

In order to reduce the effect of electrode polarization, external power must be an alternating power source, and a rectifier must be used internally. Inserting a rectifier and replacing skin in Fig. 1 with the x-type equivalent circuit result in Fig. 3. The open circuit voltage between electrodes 3 and 4, V_{34o} , is given by

$$V_{34o}=\frac{Z_5}{R_1+Z_1+Z_2+Z_5}V_1 \qquad \text{□3□}$$

When the maximum voltage amplitude of V_{34o} is larger than the sum of the internal battery voltage (V_2) and the forward voltage (V_d) of two diodes, the internal battery can be recharged. The rechargeable prerequisite can be expressed as

$$V_{34om} > V_2 + 2V_d \qquad (4)$$

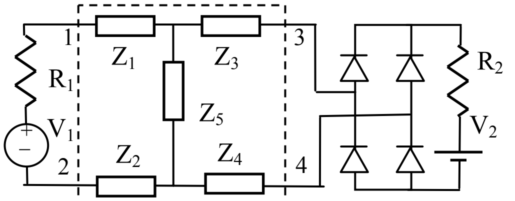

Fig. 3 AC rechargeable circuit.

Substituting (3) into (4), we have a condition for recharging:

$$V_{1m} / (V_2 + 2V_d) > |1 + (R_1 + Z_1 + Z_2) / Z_5| > 1 \qquad (5)$$

where V_{1m} is the maximum voltage amplitude of the external power source.

From (5), the following can be observed:

1. The maximum amplitude of the external voltage source must be larger than the voltage of the internal battery.
2. The internal resistance of the internal battery does not affect the condition for recharging, but the internal resistance of the external voltage source does.
3. If using an ideal voltage source (R_1=0) and ideal diode (V_d=0) , equation (5) can be simplified as

$$V_{1m} / V_2 > |1 + (Z_1 + Z_2) / Z_5| > 1. \qquad (6)$$

Define $|(R_1+Z_1+Z_2+Z_5)/Z_5|$ as the input impedance ratio (IIR), which is the ratio of input loop impedance vs. bridge impedance Z_5. This ratio determines the condition in Eq. (5)..

IV. CURRENT TRANSMISSION EFFICIENCY

Condition in (5) implies that, the best charging voltage should have a square wave, to maximize the voltage ratio at all times and make the charging process effective. Assuming that the rectifier in Fig. 3 is ideal, the internal battery branch can be placed equivalently between electrodes 3 and 4, as shown in Fig. 4. The equivalent voltage source also has a square wave, its magnitude is unchanged, and its frequency is identical to that of the external power source. Assuming that in Fig. 4 V_1, V_2, I_1, and I_2 are frequency-domain variables, we have the current transmitting efficiency:

$$\eta_I = \left|\frac{I_2}{I_1}\right| = \left|\frac{1-\dfrac{R_1+Z_1+Z_2+Z_5}{Z_5}\dfrac{V_2}{V_1}}{\dfrac{R_2+Z_3+Z_4+Z_5}{Z_5}-\dfrac{V_2}{V_1}}\right| \qquad (7)$$

Defining $|(R_2+Z_3+Z_4+Z_5)/Z_5|$ as the output impedance ratio (OIR), which is the ratio of output loop impedance and bridge impedance Z_5, the efficiency is a function of voltage ratio , IIR and OIR. Using equation (7) under two typical conditions, the current transmitting efficiency is calculated and plotted in Fig. 5 and 6.

Fig. 5 plots the efficiency curve with constant voltage ratio (V_1/V_2=4)and variations of IIR and OIR; the X-axis is IIR and the Y-axis is OIR. The efficiency increases as both IIR and OIR decrease. Its maximum value equals 100%, as both IIR and OIR approach one. This predicts that the optimization of equivalent circuit parameters is the most promising approach to increase efficiency.

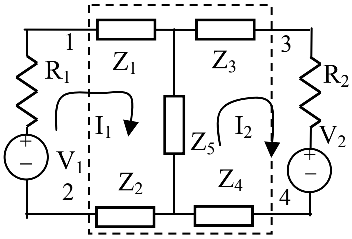

Fig.4 Rechargeable equivalent circuit.

Fig. 6 plots the efficiency with respect to the variation of both the voltage ratio (V_1/V_2) and the constant IIR and OIR (both equal to 3). The efficiency increases as the voltage ratio increases. When the voltage ratio approaches infinity, the maximum efficiency value is given by

$$\eta_{\mathrm{Im}ax} = \left|\frac{Z_5}{R_2+Z_3+Z_4+Z_5}\right| \qquad (8)$$

The output impedance ratio determines the maximum current transmitting efficiency. For a given output impedance ratio of 3, the maximum efficiency value is 33.3 %.

V. ENHANCEMENT OF CURRENT TRANSMISSION EFFICIENCY

In order to make the recharging process effective, the current flowing through the internal battery must be sufficiently large to pass adequate energy to the battery. In addition, the current transmitting efficiency value must be high. From equation (7), there are two approaches to increase the efficiency:

1. Choosing circuit impedance parameters Z_1,Z_2,Z_3,Z_4 and Z_5 to obtain the optimal input and output impedance ratio (IIR and OIR) ;
2. Increasing the voltage ratio V_1/V_2.

For the first case, when the impedance ratios both approach one, the efficiency approaches 100%. Therefore, this approach is highly effective. We can optimize the impedance ratios in three ways.

- Selecting electrode materials to decrease the contact impedances between the electrodes and the skin. This selection affects circuit impedance parameters Z_1, Z_2, Z_3 and Z_4.
- Because the permittivity and conductivity of the human skin are functions of signal frequency [4], proper selection of frequency can provide desirable permittivity and conductivity values.
- Optimizing the geometric shape and arrangement of electrodes.

Improving efficiency by increasing the voltage ratio is limited by Eq. (8). The efficiency limitation value curve is plotted in Fig. 7. When the output impedance ratio is larger than 11, the efficiency limitation value is lower than 10%. Above this, it is not useful to increase the voltage of the external power source. When output impedance ratio is less than 3, we can use the voltage-ratio to increase the current transmitting efficiency to a range higher than 30%.

The voltage ratio increases as the amplitude of the external voltage source rises. However, it will be limited by the input current tolerance of the skin. From Fig. 4, when $V_1 >> V_2$, neglecting source resistors, the input current I_1 is given by

$$I_1 = \frac{V_1(Z_3+Z_4+Z_5)}{(Z_1+Z_2+Z_3+Z_4)Z_5+(Z_1+Z_2)(Z_3+Z_4)} \qquad (9)$$

When a maximum tolerable I_1 by the skin and the equivalent circuit parameters are given, the external voltage V_1 must be limited.

Replacing the rectifier bridge in Fig. 4 with a multiple rectifier may also increase the voltage ratio. A full-wave, double-voltage rectifier circuit is shown in Fig. 8. The equivalent voltage V'₂ is

$$V_2' = \frac{1}{n}V_2 + V_d \qquad (10)$$

where n is the rectifier multiplier (n=2 in Fig. 8) and V_d is the forward voltage of the diodes. The voltage ratio increases n times when the bias voltage V_d is ideally equal to zero.

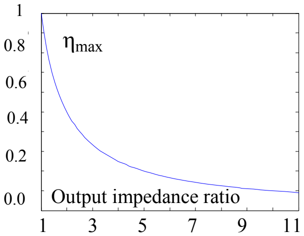

Fig.7 The efficiency limitation

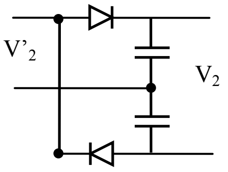

Fig.8 Full wave rectifier

VI. EXPERIMENTAL RESULTS

We have devised a circuit prototype to recharge a 3V rechargeable battery via volume conduction. The rechargeable circuit block diagram is shown in Fig. 9. The DC/AC converter converts DC voltage of battery V_s to an AC voltage, exciting the external electrodes. Through the volume conduction of the skin/tissue layer, the AC signal is transferred to the internal electrodes. Then, the AC/DC converter rectifies the signal into a DC current which recharges the internal battery. We used a lithium-ion battery (Panasonic, Type ML202) which has a nominal voltage of 3V. We drained the battery to 1.9V before the experiments started. The DC/AC converter was replaced by a square wave generator and a power amplifier. The AC/DC converter was the 2-fold full wave rectifier shown in Fig.8.

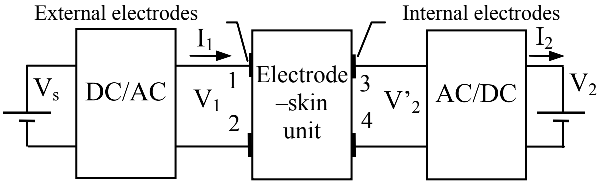

Fig.9 Rechargeable circuit block diagram

The electrode-skin unit was the most important part of the recharging system. The aim of electrode design was to decrease the input and output impedance ratios. We used rectangular electrodes with their geometric shapes shown in Fig. 10. They had three variable parameters: distance (d), width (w), and length (l) . We applied three electrode groups listed in Table 1.The internal and external electrodes had the same geometric shapes except for electrode group 3. A small piece of pig skin was utilized to construct our experimental electrode-skin unit.

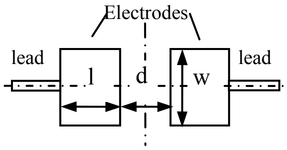

Fig.10 Electrode geometry

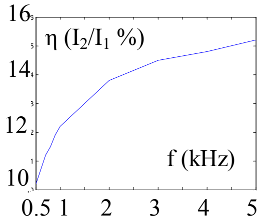

Fig.11 Result of frequent experiment

In the first experiment, we compared the charging efficiencies of two signal types (square and sinusoidal waves) using electrode group No. 1 under the condition of identical amplitude (4.1V) and frequency (1 kHz) for V_1 (see Fig. 9). Charging currents of 0.93mA for a square wave source and 0.37mA for a sinusoidal wave source were observed respectively. This indicates that the square wave source was better than that of sinusoidal source. Therefore we used square wave sources in the frequency and voltage charging experiments consecutively. In the frequency experiment the current transmitting efficiency was measured using a square wave voltage of V_1 with a constant amplitude and a varying frequency.. The resulting curve for electrode group No. 1 is shown in Fig. 11. The current efficiency increased and reached a plateau as the signal frequency increased. We chose 5 kHz as the frequency for further experiments.

The impedances between electrodes measured at 5 kHz are shown in Table 1. Using these values in Eq.(2),the corresponding impedance values of the equivalent circuit are also shown in Table 1. The IIR and OIR values are given in the last two rows.

Table 1 The parameters of electrode-skin unit

		No.1	No.2	No.3
Geometry	d(mm)	10	5	5out 5in
	w(mm)	15	15	15out 10in
	l(mm)	12	15	15out 10in
Electrode Impedance	Z_{12}(kΩ)	0.62-i0.38	0.57-i0.36	0.70-i0.44
	Z_{12}(kΩ)	0.12-i0.14	0.17-i0.20	0.32-i0.24
	Z_{14}(kΩ)	0.87-i0.46	0.50-i0.31	0.47-i0.51
	Z_{23}(kΩ)	0.55-i0.41	0.44-i0.38	0.54-i0.47
	Z_{24}(kΩ)	0.27-i0.27	0.12-i0.15	0.26-i0.24
	Z_{34}(kΩ)	0.46-i0.32	0.39-i0.23	0.52-i0.30
Circuit Parameters	Z_1(kΩ)	0.10-i0.06	0.15-i0.09	0.24-i0.11
	Z_2(kΩ)	0.00-i0.10	0.10-i0.10	0.24-i0.09
	Z_3(kΩ)	0.03-i0.09	0.02-i0.10	0.07-i0.14
	Z_4(kΩ)	0.26-i0.17	0.03-i0.05	0.01-i0.15
	Z_5(kΩ)	0.51-i0.23	0.32-i0.17	0.21-i0.25
IIR*		1.28	1.86	2.56
OIR*		1.66	1.36	1.91

We found that, if the IIR derived from the electrode design is larger than 5, the external voltage must be large, as indicated by Eq. (5). A higher external voltage resulted in a larger input current, which may burn the skin. When the OIR was larger than 10, the efficiency limit was less than 10%. These two impedance ratio cases suggested constraints on electrode design. If IIR and OIR are less than 3, a proper circuit design should result in a reasonable current transmitting efficiency.

Voltage recharging experiments have been done for all electrodes listed in Table 1. For ease of comparison, theoretical and experimental curves for electrode group No. 2 are shown in Figs.12 and 13, respectively. This group appeared to be the best design of the three. The theoretical analysis curve was approximately identical to the experimental curve. In addition, the minimum theoretical external voltage which met the recharging condition was 1.9 V (from (6) and (10) – IIR multiplied by V'_2), closely matching the experimental value of 1.8 V. This result validated the x-type equivalent circuit model. However, there was certain discrepancies due to different signal types in each case (sinusoidal vs. square wave), the nonlinearity of the diodes in the multiplier, and the measurement error.

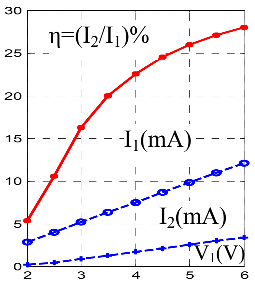

Fig.12 Calculation curve of efficiency and charging current

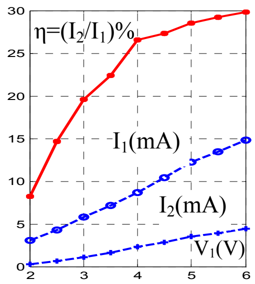

Fig.13 Experiment curve of efficiency and charging

Finally, we designed DC/AC circuit, which generated ±4.5V square wave from a source voltage V_s of 6.5V. It was able to generate a charging current I_2 of 2.8 mA to the internal battery. The experiment result is shown in Fig. 14. As a benchmark, when V_1=4.5 V, the current transmission efficiency η reached 27% with charging current being 2.8 mA (see Fig.13).

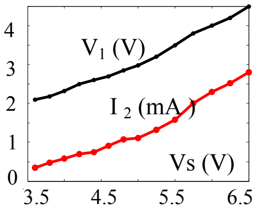

Fig. 14 charging characteristic

VII. CONCLUSIONS

In this paper, we have described our new development of a transcutaneous battery recharging circuit system that utilizes volume conduction. Through theoretical and experimental analysis, we have shown that it is an effective approach. We have also devised an x-type equivalent circuit model of the skin-electrode system, the parameters of which can be easily calculated from measurements and used to evaluate the characteristics of the recharging system, such as the recharging condition and the efficiency limit. We have analyzed the transcutaneous current transmitting efficiency by applying the x-type equivalent circuit and discussed approaches for its enhancement. Optimization of electrode design results in optimal input and output impedance ratios, which determine the recharging condition and the efficiency limit. A large voltage ratio can also enhance current transmission; however, it is limited by the current tolerance of the skin and electrode design. Finally, we have constructed a transcutaneous battery recharging circuit, which is able to pass charging current of 2.8 mA from the outside to the inside of the pig skin with a current transmitting efficiency of 27%.

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