Measurement of Energy Transmission Efficiency of Transcutaneous Energy Transformer in NaCl Solution for Ventricular Assist Devices by Reducing Common-Mode Current in the Range of 200-1500 kHz

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***Abstract*—The air-core transcutaneous energy transmission system (TETS) uses magnetic fields to transfer energy wirelessly to a ventricular assist device; the energy is transferred from a coil placed on the surface of the body (primary coil) to one inside the body. Accurate measurement of efficiency of the TETS is difficult because of the large common-mode (CM) current which flows through the ground line and the low sampling rate of the measurement equipment. In this study, a CM choke coil and a floating type measurement equipment were used to reduce the CM current flowing through the ground. Furthermore, the value of the efficiency obtained from measurements made using a floating oscilloscope with a high sampling rate was compared with the theoretical estimate of the efficiency when the transformer was kept immersed in NaCl solution to imitate the human biological tissue. In the range of 200-1500 kHz, it was possible to effectively suppress the CM current in the NaCl solution; the ratio of the primary current I_1 to the CM current I_{CM} obtained in the improved method was 21% less compared to the corresponding ratio in the conventional method. At the frequency of 500 kHz, in the NaCl solution, the maximum measured value of efficiency was 91.82%, whereas the theoretical estimate was 93.50%. The measured efficiency in the improved measurement method is in good agreement with the theoretical efficiency.**

Keywords—air-core transcutaneous transformer; wireless energy transmission; ventricular assist device; common-mode current; NaCl solution

I. Introduction

Currently, ventricular assist devices (VADs) are already being used in clinical practice in the USA, EU, and Japan. However, most of the commercially available VADs transfer energy through wires penetrating the abdomen or chest from an external source. This method reduces the patient's quality of life and increases the risk of acquiring infectious diseases [1]. To overcome these problems, the air-core transcutaneous energy transmission system (TETS) has been studied by several researchers [2].

The air-core TETS is composed of two coils with spirally wound conductive wires, placed facing each other: one outside (primary) and the other inside (secondary) the abdomen or chest. It is necessary to reduce the power loss of the transformer and increase transmission efficiency. There have been several studies that have aimed at achieving a high efficiency of the TETS, and some of them have reported an efficiency of 96 % or more by measurement [3]. However, there is some uncertainty in these values, because there are no reports on comparison between the measured value and theoretically estimated value calculated from the equivalent circuit of the TETS. Two problems are expected in the measurement of efficiency: one is CM currents [4] that flow between the primary and secondary coils and ground because of capacitive coupling of these coils and the measurement equipment connected to the ground; the other is the measurement accuracy of the equipment in the frequency range of 1000 kHz and above.

In this study, a CM filter and a floating type measurement equipment against ground line (the battery of the uninterruptible power supply (UPS)) were used to suppress the CM current. Moreover, an oscilloscope having a sampling rate in the GHz range and a differential probe having a common mode rejection ratio (CMRR) of -60 dB or more were used in the frequency range of 1000 kHz and above.

Air-core coils covered by a polyethylene terephthalate (PET) insulation sheet were kept immersed in NaCl solution (0.22 S/m) to imitate the wet skin, and the CM current and energy transmission efficiency using this coil in the NaCl solution were measured with our the improved measurement method.

II. Methods

A. Air-core transcutaneous transformer

Figures 1 (a) and (b) show the view of the air-core coils used in the TETS and the block diagram of the air-core TETS, respectively. The direct current supplied by a dc power source or a secondary battery outside the body is converted to alternating current with a frequency of 100-1500 kHz using a switching circuit. The ac power is then transmitted inside the body through electromagnetic induction between the air-core coils placed inside (secondary) and outside (primary) the body. Table I lists the parameters of the air-core coils. The coils are made of copper litz wire considering the skin-effect. The primary coil has an outside diameter of 90 mm (35 turns), an

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inside diameter of 20 mm, and thickness of 1 mm. The secondary coil has an outside diameter of 60 mm (20 turns), an inside diameter of 20 mm, and thickness of 1 mm. The secondary coil is suitable for implants, because it is a thin, lightweight, and pancake-shaped coil. However, when the coils are misaligned, the coupling coefficient decreases and the efficiency decreases [5].

In this study, the air-core coils were covered by a PET insulation sheet (0.6 mm thick), because they were immersed in NaCl solution to imitate the implantation in the human body. Figures 1 (c) and (d) show the transformer covered by PET sheet and the one immersed in the NaCl solution, respectively. The distance between the primary and secondary coils was fixed at 9.2 mm (the coupling factor between the primary and secondary coils is approximately 0.44). The conductivity of the NaCl solution was adjusted to 0.22 S/m to imitate the conductivity of wet skin, because it is assumed that secondary coil is implanted in wet skin [6]. The conductivity was adjusted with a conductivity meter (CUSTOM, CD-6021).

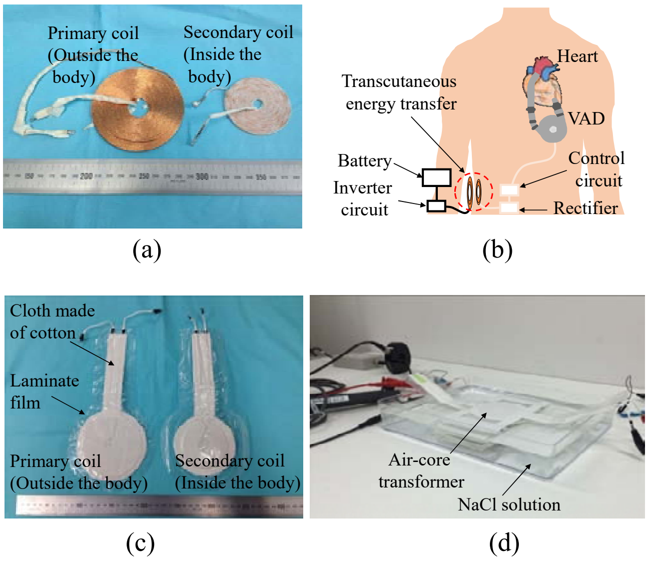

Fig. 1. (a) Views of air-core coils, (b) Block diagram of air-core TETS, (c) Transformer covered by PET, and (d) Transformer immersed in NaCl solution.

Table Ⅰ. Parameters of the air-core coils.

Coil details	Primary	Secondary
Outside diameter [mm]	90	60
Inside diameter [mm]	20	20
Number of turns	35	20
Litz wire diameter [mm]	0.03	0.03
Number of litz wires	504	1008
Distance between the coils [mm]	9.2	

B. Suppression of common-mode current

The path of the CM current in the TETS is depicted schematically in Figure 2. Passive probe is widely used and R_L is the resistance of the load resistor to imitate the ventricular assist device. It is assumed that CM currents flow between the primary and secondary coils owing to capacitive coupling of these coils, and flow through the ground line of the measurement equipment such as oscilloscope. With the above assumption, the following instruments were used.

(i) CM filter is inserted in front of the primary coil (Daishinmusen, DCF-RF37-BCL, Attenuation: -60 dB at 1000 kHz)

(ii) For the secondary side, an oscilloscope which floats on the ground by using the battery of the uninterruptible power supply (APC, smart-UPS1000) is used.

(iii) High CMRR differential probe is used (Agilent, N2791A, CMRR: -40 dB/Pico, TA045, CMRR: -55 dB at 1000 kHz)

Figure 3 shows the measurement circuit applied using (i), (ii), and (iii). L_1 and L_2 are the primary and secondary inductances, respectively, and C_1 and C_2 are the primary and secondary capacitances, respectively. To transmit a large amount of power to the VAD, the transformer requires resonance capacitances C_1 and C_2, which resonate with inductances L_1 and L_2, respectively.

The CM currents and transmission efficiencies with the improved and conventional methods were compared. CM current suppression is adequately considered in our proposed method, while the conventional method uses only instrument (iii).

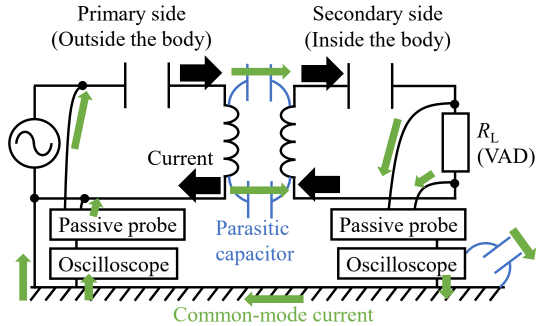

Fig. 2. The path of CM current in TETS.

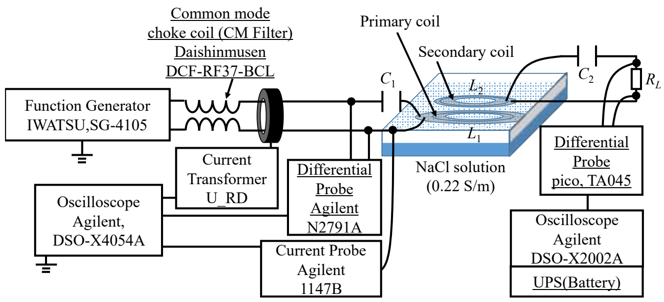

Fig. 3. Measurement circuit applied using instruments (i), (ii), and (iii).

C. Theoretical estimate of energy transmission efficiency in NaCl solution

Figure 4 shows the equivalent circuit of the transformer in NaCl solution. The theoretical estimate for transmission efficiency is obtained by the following equation.

$$\eta = \frac{\omega^2 M_s{}^2 R_L}{(r_{L1}+r_{C1})\{(r_{L2}+r_{C2})+R_L\}^2+\omega^2 M_s{}^2\{(r_{L2}+r_{C2})+R_L\}} \qquad (1)$$

where ω is the angular frequency, M_s is the mutual inductance in NaCl solution, R_L is the value of the load resistance; and r_{C1} and r_{C2} are the loss resistance of the primary and secondary capacitances, respectively. Furthermore, r_{L1} and r_{L2} are the primary and secondary winding resistances, respectively, including the loss factor of eddy current, when the air-core transformer is immersed in NaCl solution. For the theoretical calculation, an LCR meter (HIOKI, IM3536) was used to measure the load resistance, inductance, winding resistance, etc. L_1, L_2, r_{L1}, and r_{L2} were measured when the air-core transformer is immersed in NaCl solution. The mutual inductance M_s and the coupling coefficient k_s in NaCl solution were measured as per JIS C5321 [7]. C_1 and C_2 values were calculated using Eq. (2).

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} = \frac{1}{2\pi\sqrt{L_2 C_2}} \tag{2}$$

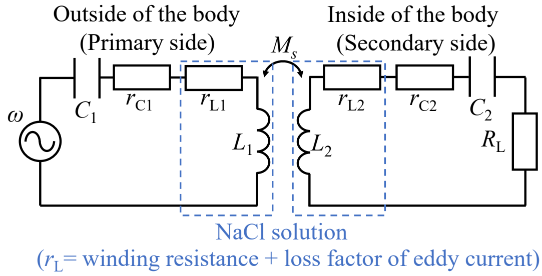

Fig. 4. Equivalent circuit of transcutaneous transformer in NaCl solution.

D. Measured values of CM current and energy transmission efficiency

The CM current was measured using a high frequency current transformer (U_RD, CTL-28-S90) to evaluate the attenuation of the CM current. A current transformer was inserted between the function generator and the transformer, and the two lines were clamped together (Figure 3).

Furthermore, the energy transmission efficiency was obtained under the conditions described in section II B and Figure 3. It was calculated using the following equation.

$$\eta = \frac{\frac{V_2^2}{R_L}}{V_1 I_1 cos\theta_1} \tag{3}$$

where V_2 is the secondary voltage across the load resistance, V_1 and I_1 are the primary voltage and primary current, respectively, and θ_1 is the phase difference between V_1 and I_1.

III. Results and Discussion

A. Result of CM current measurements

Figure 5 shows the ratio of primary current I_1 to CM current I_{CM}, obtained from the current measurements in NaCl solution, as a function of frequency. From the result, it can be seen that the ratio is less than 3% in the improved method, as against 23% in the conventional method, at a frequency of 1500 kHz. It can also be seen that the CM current is effectively suppressed. In addition, the ratio increased with the increase in frequency. The reason could be that the capacitance between the coils in NaCl solution increased dramatically as the frequency was increased. Furthermore, the CM current in the conventional method was larger than that in the improved method at all frequencies.

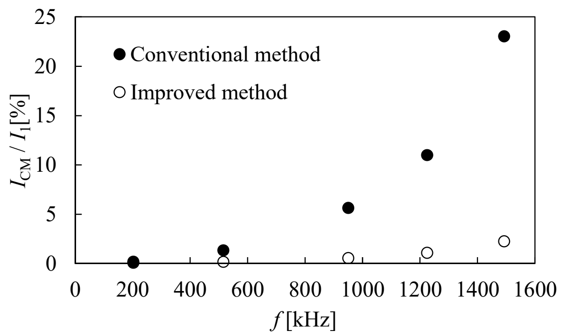

Fig. 5. Ratio of CM current in NaCl solution obtained from measurement results.

B. Measured values of the parameters in NaCl solution for obtaining theoretical estimate

Figure 6 shows the self-inductance L_1, L_2, and mutual inductance M_s as a function of frequency. Figure 7 shows r_{L1} and r_{L2} of the primary and secondary coils, respectively. The values of r_{L1} and r_{L2} in air indicate only winding resistances. They increased slightly as the frequency was increased. The values of r_{L1} and r_{L2} in NaCl solution include both winding resistance and loss factor of eddy current. The value of r_{L1} in NaCl solution increased sharply as the frequency was increased. It is expected that the eddy current loss in NaCl solution significantly affects transmission efficiency. In the next chapter, the theoretical transmission efficiency is calculated using these values.

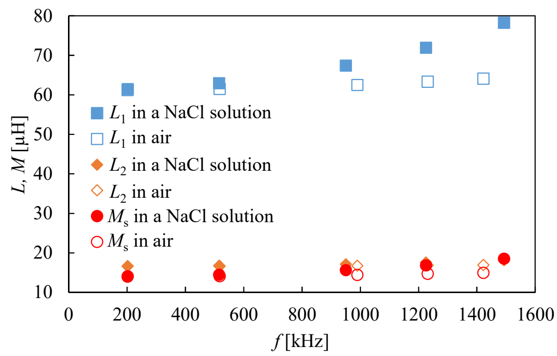

Fig. 6. Self-inductance L_1, L_2, and mutual inductance M_s as a function of frequency.

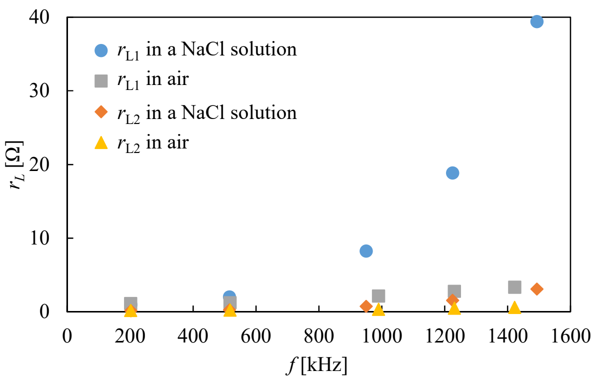

Fig. 7. Loss factor of primary and secondary coils r_{L1} and r_{L2} as a function of frequency.

C. *Results of the comparison of measured and theoretical values of AC/AC energy transmission efficiency*

Figure 8 shows the AC/AC energy transmission efficiency η as a function of frequency. All plots are mean of five measurements and standard deviation is shown as error bar in Figure 8. It can be seen that our method is very accurate because all error bars are very small.

There is no large difference between the theoretical and measured efficiencies in the improved method at all frequencies. However, above 1000 kHz, there is a large difference between the theoretically estimated efficiency and the measured efficiency in the conventional method.

The measured efficiency in the improved method is in close agreement with the theoretical estimate. Considering the large CM current in the conventional method, as seen in Figure 5, the efficiency in the conventional method at frequencies above 1000 kHz will have a large error, because the large CM current may induce large leakage power from the transformer to the ground.

The maximum measured efficiency in NaCl solution was 91.82% at a frequency of 500 kHz. In practical applications, it is necessary to consider the biological effect of the electromagnetic field induced from the transformer. Considering this effect (the internal electric field and specific absorption rate in human body), it can be stated that the frequency of 500 kHz lies in the safe frequency band [8].

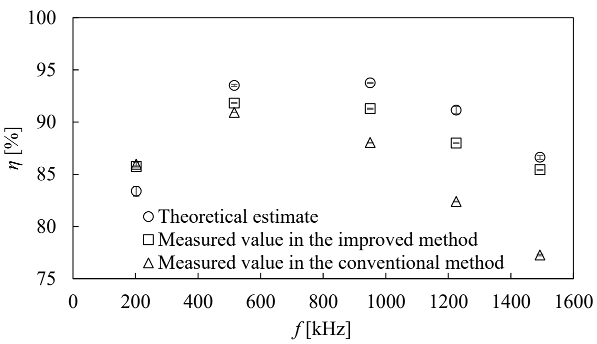

Fig. 8. AC/AC energy transmission efficiency.

IV. Conclusion

In this study, an accurate method for the measurement of efficiency of the air-core transcutaneous transformer was attempted considering CM current. The ratio of primary current I_1 to the common-mode current I_{CM} in NaCl solution was less than 3% in the improved method, in which a CM choke coil, differential probe, and UPS were used. It can be seen that the common -mode current could be effectively suppressed.

In addition, the measured value of the AC/AC energy transmission efficiency was compared with the theoretical estimate. The maximum efficiency in NaCl solution in the improved method was 91.82% at the frequency of 500 kHz. Moreover, the measured value was closer to the theoretical estimate in the improved method than in the conventional method.

In future, the possibility of further reduction in the difference between the measured value and theoretical estimate needs to be examined. It is necessary to design the equivalent circuit considering the resistance and capacitive factor of the human tissue between the coils, and design a more accurate equivalent circuit for the transformer to suit the human tissue.

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