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A New Control Method Depending on Primary Phase Angle of Transcutaneous Energy Transmission System for Artificial heart

H. Miura, I. Saito, F. Sato, Y. Shiraishi, member, *IEEE,* T. Yambe, member, *IEEE,* and H. Matsuki, member, *IEEE*

Abstract— **A new control method for stabilizing output voltage of the transcutaneous energy transmission system for artificial heart is proposed. This method is primary side, is outside of the body, which is not depending on a signal transmission system from the implanted device. The impedance observed from primary side changes from inductive to capacitive and the output voltage decreases drastically when the output current is large and the coupling factor is higher than that of the optimal condition. In this case, the driving frequency should be changed to higher so that the phase angle of the primary impedance is zero degree. The preliminary examination showed that this control method can enhance the output voltage limit to twice and the feasibility of the primary side control.**

I. Introduction

The best treatment for the end-stage heart failure is currently heart transplantation. However, the shortage of donor hearts and the esthetical problem are serious, especially in Japan. Total artificial hearts (TAHs) and ventricular assist devices (VADs) have been developed as alternatives to the transplantation. Percutaneous leads should be avoided in long-term implantations due to the risk of infection and patients' quality of life, transcutaneous energy transmission system (TETS) which transmits energy using a pair of coils via intact skin was proposed [1].

We have developed TETSs for the left ventricular assist devices [2] and other internal artificial organs [3]. TETSs that were used or under development had/have air cored coils and conventional diode rectifiers [4] [5]. The system we have been developed has thin Mn-Zn ferrite cores, which increase the magnetic coupling and self-inductance [5]. Also, the magnetic shield effect of the core made it possible to mount the rectifier circuit board in the internal space of the internal coil core. Thus, the number and total volume of the implanted devices were reduced. The size of the implanted device was 72mm diameter and 33ml volume. And thin and flexible DC interconnection cable could be used instead of the thick and stiff AC wire. In addition, MOSFET synchronous rectifier using a phase-locked loop (PLL) [6] was used to reduce diodes' power consumption. The system achieved the DC-DC maximum efficiency of 93.4% [7].

H. Miura, Y. Shiraishi and T. Yambe are with Institute of Development, Aging and Cancer, Tohoku University, Sendai, Miyagi 9808575 JPN (corresponding author to provide phone:+81-22-717-8517; fax: +81-22-717-8518; e-mail: h.miura@ idac.tohoku.ac.jp).

I. Saito is with the University of Tokyo, Bunkyo-ku, Tokyo, JPN.

F. Sato is with the graduate school of Engineering, Tohoku University

H. Matsuki is with the graduate school of Biomedical Engineering, Tohoku University

The stability of output voltage is one of the most important problems for TETS, the output voltage of the TETS decreases when the primary coil shifts from the normal position, and rotary blood pumps are actuated by DC brushless motors, which needs higher electric power when they are started or the bearing friction is increased. In the previous development, any control system for stabilizing output voltage was not used for our TETS. Because, in the point of view of reliability and robustness, a feedback control depending on signal transmission system from the internal unit to outer unit should be avoided. Our first approaches were to optimize the coil geometry [8] and the setting of electrical and magnetic parameters [9]. In this paper, we propose and examine a new control method for stabilizing output voltage of the TETS for artificial organs with features, primary side (outside of the body) control without signal transmission system and extra power switching device and no transmission efficiency reduction .And the implementation is thought to be simple.

II. Methods

A. Configuration of TETS

Totally implantable artificial heart system consists of external and internal butteries, inverter, the outer and inner coils and rectifier etc. as shown in Fig.1. When, the outer coil is detached from the body, electrical power is supplied from the internal battery. Fig.2 shows the TETS we have developed.

B. Analysis of the transfer characteristics

The TETS can be analyzed by simplified linear circuit model shown in Fig.3.In this model the equivalent coil resistance and iron loss are assumed to be negligible because they are much small than the load resistance. To compensate leakage inductance, a capacitor is inserted to the primary side in series. The compensation capacitors are suffered from higher stress, the capacitor in the secondary side should be eliminated because of its size and failure. Explanations of parameters are shown in table 1.

Parameters that can be measured directly from outside the body are V_{in} and the primary current I_{in} and the impedance seen from primary side Z_{in} is calculated from V_{in} / I_{in}. The control method is a primary side control, which is not depending on the signal transmission system but based on the phase angle of Z_{in}, frequency can be changed easily utilizing voltage controlled oscillator (VCO). The coupling factor k varies because the coil position is shifting. The load R varies depending on the demand of the power consumption of the pump.

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Gain G of the input voltage to output voltage V_{out}/V_{in} is can be written as

$$\left|\frac{V_{out}}{V_{in}}\right| = \left|\frac{\omega k\sqrt{L_1 L_2}R}{\left(\omega L_1 - \frac{1}{\omega C}\right)R + j\omega L_2\left\{\omega L_1(1-k^2) - \frac{1}{\omega C}\right\}}\right| \equiv G \quad \text{- (1),}$$

the impedance Z_{in} seen from primary side is written as

$$Zin = \frac{\omega^2 k^2 L_1 L_2 R}{R^2 + \omega^2 L_2^{\;2}} + j\left\{\frac{\omega^3 L_1 L_2^{\;2}\left(1-k^2\right) + \omega L_1 R^2 - \frac{R^2 + \omega^2 L_2^{\;2}}{\omega C}}{R^2 + \omega^2 L_2^{\;2}}\right\} \quad (2),$$

and phase angle[1] of Z_{in} is written as

$$\theta = \tan^{-1}\left\{\frac{\omega^3 L_1 L_2^{\;2}\left(1-k^2\right) + \omega L_1 R^2 - \frac{R^2 + \omega^2 L_2^{\;2}}{\omega C}}{\omega^2 k^2 L_1 L_2 R}\right\} \quad (3).$$

Considering coupling factor k is the variable parameter, the condition of the load characteristics is classified into 3 states by the value of the coupling factor k. (Fig.4).

a. When the coupling factor k satisfies

$$k = \sqrt{1 - \frac{1}{\omega^2 L_1 C}} \equiv k_0 \quad (4)$$

This is the optimal condition; the coupling factor is defined as k_0, the equivalent output impedance of the TETS is zero. Load characteristics are flat and stable. Setting of k_0 is an important problem for Design of TETS, in our previous study; it was found that the optimal condition should be chose at wider coil distance g, in that case g = 15mm was chose [5].

b. When coupling factor k is greater than that of the optimal condition.

$$k \geq k_0 \,(5)$$

In this state, distance between the coils is close. As the load R decreases, the phase angle decreases from +90 degrees to -90 degrees to a monotone decrease. In other words, Z_{in} changes from inductive to capacitive. When Z_{in} is capacitive, the output voltage drastically decreases.

c. When coupling factor k is smaller than that of the optimal condition

$$k \geq k_0 \,(6)$$

In this state, the coil distance is wider from the optimum condition, Z_{in} is always inductive. The phase angle is always positive, and has a local minimum.

C. Control method

In the state *c*, when the system has a larger coupling factor k, the relationship between the output voltage and the phase angle by the means of changing the driving frequency f can be analyzed from (1)-(3), Maximum output voltage is obtained when the phase angle is zero degrees (Power factor PF =1.) the phase angle changes from -90degrees to +90degree in a monotone increase as the driving frequency *f* increases (shown in Fig. 5).

Driving frequency f_0 is set to satisfy the optimal condition when the coil distance g is wider side of the operating region. Only when the phase angle is negative, driving frequency *f* is increased so that the phase angle is zero.

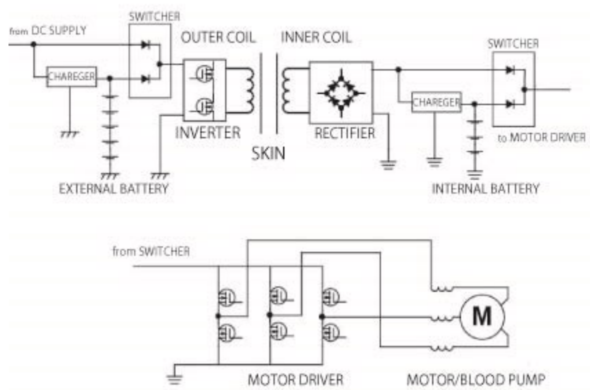

Fig.1. A electrical diagram of totally implantable artificial heart system

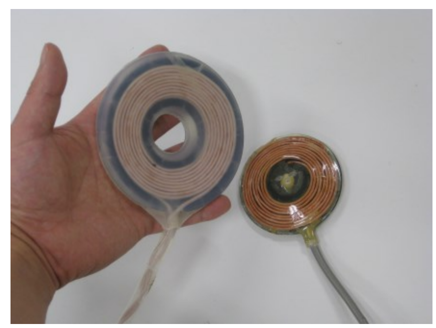

Fig.2. Transcutaneous Energy Transmission System

Outer coil: 100mm diameter (Left). Inner coil: 72mm diameter (Right)

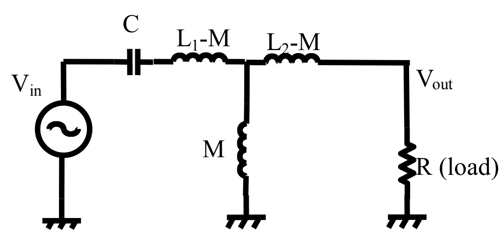

Fig.3. Simplified linear circuit model of TETS

III. EXPERIMENTS

To examine the proposed control method, we performed fundamental experiment. The input voltage & current, the output voltage & current and the phase angle of the input were measure by power meters (Yokogawa Electric Corp. Tokyo, Japan). As a power source, a function generator (NF Corp. Yokohama, Japan) and a power amplifier (NF Corp. Yokohama, Japan) were used. The Waveform was sinusoidal and the frequency was controlled manually. A non inductive register array was used for variable load. The Coil parameters are shown in the table. 2. The Coil distance *g* was changed to

0, 5, 10, 15 and 20mm. Load R was varied from 2 to 100 ohms.

IV. RESULT

A. Load characteristics without the control

Load characteristics are shown in Fig. 6, 7. In Fig. 6, the horizontal axis shows load R, the vertical axis shows $|V_{out}/V_{in}|$ G, the parameter is the coil distance g =0, 5, 10, 15, and 20mm. Driving frequency was constant and set to f_0 = 168 kHz. When g=15mm, the optimal condition was satisfied, the output voltage was flat in the normal load range. Phase angle approached to zero as the load R was smaller (Fig. 7). However in the heavier load condition, slight voltage drop was found, it was because of the coil resistance, iron loss and a slight shift from optimal condition. When g =0, 5, and 10 mm the phage angle became smaller as the load R was smaller, after the phase angle became smaller than zero then the voltage dropped obviously.

B. Load characteristics with the control

Load characteristics with the control are shown in Fig. 8. To keep the phase angle zero, the frequency was changed. Phase angle changes under the control are shown in Fig. 9. Phase angle stayed at zero when the load R was small. Also the driving frequency change is shown in Fig. 10. This control method can enhance the output voltage limit to twice at g =5mm.

TABLE I. EXPLANATION OF PARAMETERS

Sym bol	Name	Unit	Discription
V_{in}	Input voltage	V	Constant
V_{out}	Output voltage	V	Variable
C	Compensation capsitance	F	Constant
G	Gain $\lvert V_{out}/V_{in}\rvert$		
L_1	Self indutance of primary coil	H	In the analysis, assumed to be constant
L_2	Self indutance of internal coil	H	
M	Mutual inductance	H	$M=k\sqrt{L_1L_2}$
R	Load resistance	Ω	variable
G	distance between the coils	mm	
k	Coupling factor	-	variable depending on coil position
k_0	Coupling factor for the optimal condition		
f	Driving frequency	Hz	controllable
f_0	Normal driving frequency	Hz	
ω	Angular frequency	rad/sec	$\omega=2\pi f$
θ	Phase angle of input voltage & current	degree	

TABLE II. COIL PARAMETERS

g(mm)	L_1(uH)	L_2(uH)	k
0	53.93	12.65	0.72
5	51.03	9.79	0.58
10	46.61	9.11	0.47
15	45.35	8.70	0.37
20	44.79	8.52	0.27

V. DISCUSSION

Resonant control systems which change driving frequency to lock the phase angle to zero have been previously proposed. Yet, these systems have to be combined with pulse width modulation (PWM) control and feedback system, via signal transmission system from internal devices [11]. The zero volts switching (ZVS) is the optimal condition for the bridge inverters to minimize the switching loss. However, resonant system has the critical resonant condition of over current and voltage when the pump stops or the outer coil is detached. In this control, basically works at f_0, even when the control is active, f is always higher than f_0, the system do not lapse into the critical resonant condition.

This study focused on the linear theoretical analysis, so this study has several limitations and future works. The analysis was brief, so, more precise consideration has to be reported. Also, dynamic response must be considered. And we have to implement this control in an actual circuit; a phase detector (PD) in the switching circuit might have some error from the sinusoidal wave. However the system is thought to be simple, the PD controls VCO with lower frequency limit set to f_0 so that the phase angle is zero.

VI. CONCLUSION

New control method for TETS is proposed, the analysis and the experiment showed the feasibility of primary side control to enhance the operating range of TETS.

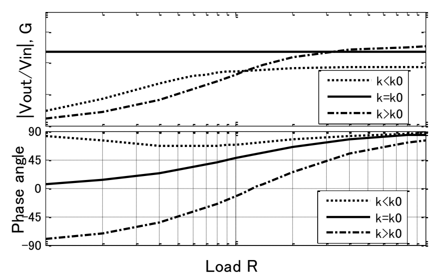

Fig.4. Change of the output voltage and phase angle of input voltage & current vs. load R

Horizontal axis is load R, vertical axes are the gain G (above) and the phase angle θ (bottom). The parameter is coupling factor k which corresponds to the coil distance g.

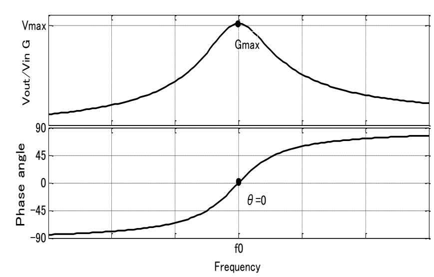

Fig.5. Change of the output voltage and phase angle of input voltage &current vs. driving frequency.

Horizontal axis is frequency, vertical axes are the gain G (above) and the phase angle θ (bottom). G takes the maximum at θ=0.

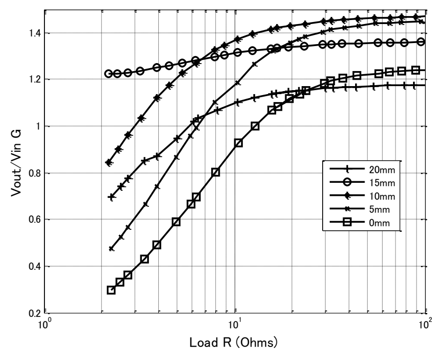

Fig.6. Load characteristics without the control.

Horizontal axis is Load R, vertical axis is the gain G. G decreased obviously when load R was small and g was not 15mm (optimal condition).

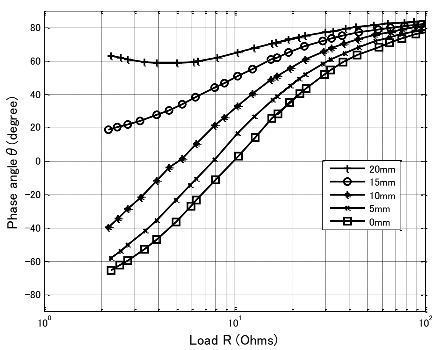

Fig.7. Phase angle θ vs. Load R.

Horizontal axis is Load R, vertical axis is phase angle θ .

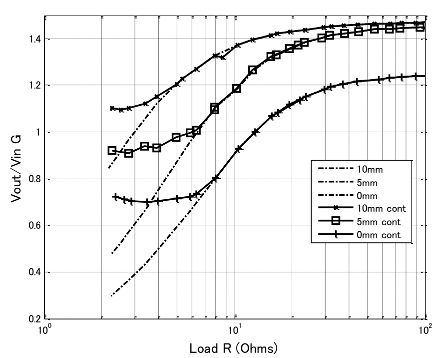

Fig.8. Load characteristics with the control

Dashed-lines show load characteristics without the control. The effect of the control is clear at the lower resistance region.

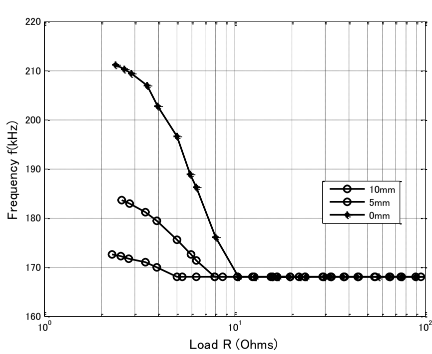

Fig.9. Frequency changes under the control

Horizontal axis is load R, vertical axis is the frequency. The frequency was increased so that θ was locked to zero.

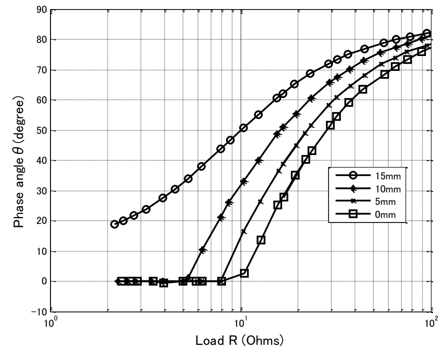

Fig.10. Phase characteristics under the control

Horizontal axis is load R, vertical axis is the phase angle θ.θ was locked to zero when θ is below zero at the normal operating frequency of 168 kHz.

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