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Wireless Energy Transmission System Based on LLC Resonant Converter

***Abstract**. This paper presents a wireless transcutaneous energy transmission system based on LLC topology. Because the coupling coefficient of the transformer is not good as normal transformer, a resonant converter is required for the transcutaneous energy transmission system. This paper proposed a transcutaneous energy transmission system based on the LLC type resonant converter rather than traditional SS or SP resonant converter. Finally, an experimental prototype is set up to validate advantages of LLC type transcutaneous energy transmission system.*

***Streszczenie.** W artykule zaprezentowano metodę bezprzewodowej transmisji energii bazującej na obwodzie LLC. Dla poprawienia sprzężenia zastosowano obwód rezonansowy. Przedstawiono badania eksperymentalne systemu. (**Bezprzewodowa transmisja energii bazująca na rezonansowym obwodzie LLC**)*

Keywords: *transcutaneous energy transmission system, LLC, resonant converter*
Słowa kluczowe: bezprzewodowa transmisja energii, obwód LLC..

Introduction

The transcutaneous energy transmission system (TETS) is designed to deliver power efficiently to implanted biomedical devices, such as artificial hearts and cardiac assist devices from out of patients' body through electromagnetic coupling technology [1]-[5]. As an emerging technology, TETS has drawn scientists and researchers' attention in the world. Since 1990th, Prof. J. T. Boy's group in Auckland University has done lots of works on TETS [1]. Stefan V. Mollov from University of Birmingham has carried out research into remote energy transfer for artificial human implants [3]. Experiments on TETS for artificial hearts have been performed by Shinsuke Arai's group in Japan [7]-[10].

Because there is a gap between primary side and secondary side of the loosely coupled transformer, the mutual coupling inductance is generally weak. As a result, the power transferred to the secondary side is relatively low. So a resonant tank should be added into the TETS. Traditional resonant tank include SS, SP, PS and PP compensated nets, which added one capacitor both on the primary side and secondary of the loosely coupled transformer [11] [12]. In this paper a TETS based on LLC converter is discussed, which need only one primary side compensation capacitor. Therefore this system can reduce the circuit volume implanted in the patient's body. As a promising topology, LLC resonant converters can achieve both high efficiency and wide input voltage range capability because of its voltage gain characteristics and little switching loss. Furthermore, it has the advantage of both zero voltage turn-on switching for primary side switches and zero current turn-offs switching for secondary diode-rectifiers [13].

In this paper, firstly, the model of the proposed LLC resonant TETS is constructed. Then, the operation principle and switching features are discussed. Finally, some measured results are given to verify the advantages of the proposed LLC resonant TETS.

Circuit implementation

The typical structure of the TETS shown in Fig. 1 consists of the inverter, the loosely coupled transformer [11] [14], the compensation components and the rectifier. The resonant converter generates high frequency sinusoidal current, and then, the time-varying electromagnetic fields yielded by the primary coil of transformer induce a voltage in the secondary coil. Thus, power is transmitted to the biomedical device from out of the skin.

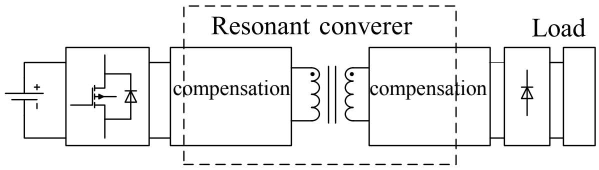


Fig.1. Schematic of the TETS

Fig. 2 shows the schematic of the TET system studied in this paper. Because the power is not high for the TET system, a half bridge inverter is chose in this case. In addition, the full wave rectification circuit with a center-tapped is used to reduce the size of the TET system inside the human body.

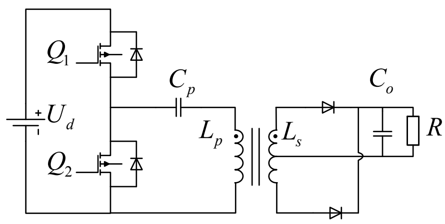


Fig.2. Schematic of proposed half bridge TETS

It can be seen from Fig. 2, the square wave voltage is produced at the mid-node of the half bridge inverter by driving switches Q_1 and Q_2 alternately with 50% duty cycle. The resonant tank consists of the resonant capacitor and the loosely coupled transformer. In the resonant tank, only sinusoidal current is allowed to flow through it because the network filters the higher harmonic currents. A full wave rectifier is connected at the secondary winding of the transformer.

For the purpose of modelling the LLC resonant converter, the transformer model of the TETS should be deduced first. About the TETS, the mutual inductance model is usually analysis for SS or SP compensated resonant tank but it is not fit for LLC resonant tank because the LLC tank is two elements resonant converter, in which the leak inductance and magnetizing inductance involve in the resonant process during different working mode. The T-type transformer model is better for the analysis of LLC resonant inverter. To analyze the LLC resonant tank, the mutual inductance coupling model should be transfer to the T-type transformer model, which is shown in Fig. 3.

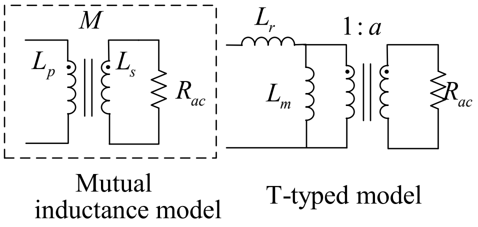


Fig.3. Transformer model of TETS

In Fig. 3, M is the mutual inductance of the primary winding and secondary winding of the loosely coupled transformer, R_{ac} denotes the equivalent AC load resistor. In the mutual inductance model, L_p and L_s represent the primary winding inductance and secondary inductance respectively. In T-type model, L_r and L_m stand for the leakage inductance and the magnetizing inductance of the transformer. In addition, an ideal transformer is paralleled with the magnetizing inductance to transfer power to the load. The parameters relation of mutual inductance model and T-type model is shown as following.

(1) $$L_m = k^2 L_p$$

(2) $$L_r = (1-k^2)L_p$$

(3) $$a = \frac{L_p}{M}$$

In which, k is the coupling coefficient which can be calculated as

(4) $$k = \frac{M}{\sqrt{L_p L_s}}$$

Thus, the TET system based on LLC resonant converter is modelled presented as Fig. 4.

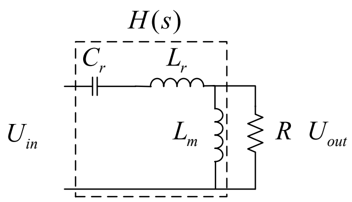


Fig.4. LLC model of proposed TETS

The LLC resonant at the primary side has two resonant frequencies. One is determined by the resonant components Lr and Cr. The other is determined by the Lr, Lm and Cr. The two resonant frequencies are shown as follows:

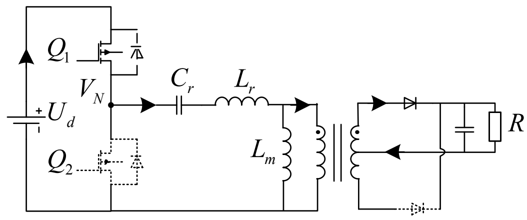
(5) $$f_{r1} = \frac{1}{2\pi\sqrt{(L_m + L_r)C_r}}$$

(6) $$f_{r2} = \frac{1}{2\pi\sqrt{L_r C_r}}$$

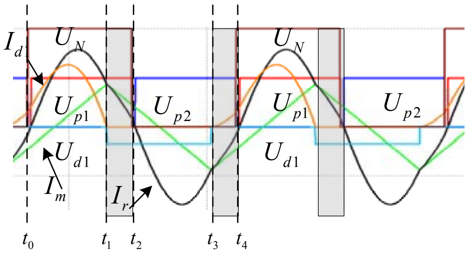
Operation principle of LLC converter

Fig. 5 illustrates the typical waveforms of the LLC converter. It is assumed that the operation frequency is between f_{r1} and f_{r2} which is the optimal operation mode for primary switches and secondary rectifier diodes.

It is worth to mention that the LLC resonant inverter has two different resonant modes [15]. The first resonant mode is during the time from t_0 to t_1, in which the capacitor C_r and leak inductance L_r take part in resonant. During this mode, leak inductance current I_r increase as sinusoidal waveform. But magnetizing inductance current I_m linearly increases because it is clamped by output voltage. When I_m is equal I_r at t_1, the secondary resonant mode occurs, which is resonant between C_r and L_r in series with L_m. This resonance continues till switch Q_1 turned off at time t_2. During the secondary resonant time period, the output current remains zeros. So the secondary rectifier diodes operate naturally at zero current switches. Moreover, it can be seen that the current I_r lags the inverter voltage U_N, which allows the MOSFETs to be turned on with zero voltage, and therefore turn-on loss is minimized. So, if LLC resonant inverter works in optimal mode, it can work with high efficiency [16] [17].



(a)Topology of LLC Resonant Converter



(b) Steady State Waveform of LLC Resonant Converter

Fig.5. LLC Resonant Converter

Based on the fundamental harmonic approximation (FHA) method, the input voltage of LLC resonant tank is shown in equation (7), where U_{dc} is the input dc voltage.

(7) $$U_{in} = \frac{\sqrt{2}}{\pi} U_{dc}$$

As seen form fig.4, the input impedance of resonant tank can be deduced as equation (8).

(8) $$Z_{in} = \frac{1}{sC_r} + sL_r + R_{ac} // sL_m$$

Furthermore, the transfer function of output voltage can be expressed in equation (9).

(9) $$H(s) = \frac{R_{ac} // sL_m}{Z_{in}}$$

Then, the input-to-output dc-dc voltage conversion ratio is equal

(10) $$M = \frac{U_{out}}{U_{in}} = H(s)$$

By applying the relationships of equation (7) to equation (10), the LLC resonant converter voltage gain can be expressed as (11) [13].

(11) $$M(f_n, \lambda, Q) = \frac{1}{\sqrt{\left(1+\lambda-\frac{\lambda}{f_n^2}\right) + Q^2\left(f_n - \frac{1}{f_n}\right)^2}}$$

In which,

(12) $$f_r = \frac{1}{2\pi\sqrt{L_r C_r}}$$

(13) $$f_n = \frac{f}{f_r}$$

(14) $$\lambda = \frac{L_r}{L_m}$$

(15) $$Q = \sqrt{\frac{L_r}{C_r}} \Big/ n^2 R_{ac}$$

Where, f_r is the resonant frequency, f_n is defined as frequency ratio, Q is quality factor and λ denote the ratio of magnetizing inductance to resonant inductance respectively. The gain characteristics of LLC converter at different loads are shown in Fig. 6.

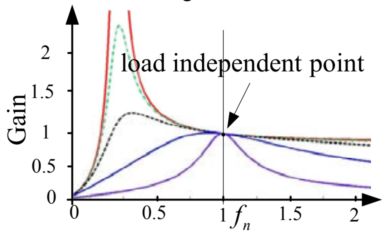


Fig.6. DC characteristic of LLC converter

It can be seen from Fig. 6 that the voltage gain is equal to 1 for all load conditions at resonant frequency. When the frequency is higher than the resonant frequency, the gain is always less than 1, and the zero voltage switching for primary switches can be achieved. When the switching frequency is lower than the resonant frequency, either ZVS or the zero current switching (ZCS) for the primary switches can be achieve, and frequency of the maximum gain is the critical point. When operation frequency is above the critical point and below the resonant frequency, the zero voltage turn-on for primary switch and zero current turn-offs for secondary diodes can be achieved simultaneously. For MOSFETs, the ZVS operation is preferred. So, it is the optimal operation mode during this frequency.

Experimental results

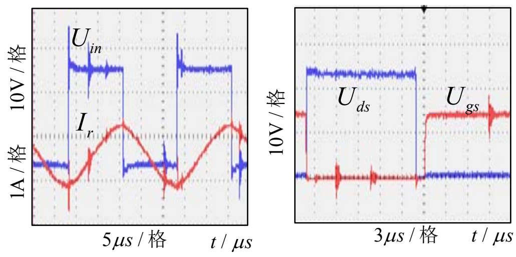
A TETS based on LLC resonant converter is fabricated. The system topology is as Fig. 2 and the parameters are as follows:

Table 1. Parameters of proposed prototype circuit

Item	Symbol	result
Input voltage	V_{in}	12 V
Output voltage	V_{out}	4.2V
Load	R	10.5 Ω
Coupling coefficient	k	0.75
Primary self-inductor	L_1	45 μH
Secondary self-inductor	L_2	39 μH
Parallel resonant inductor	L_m	21 μH
Series resonant inductor	L_r	24 μH
Resonant capacitor	C_r	53nF
Filter capacitor	C_f	22 μF
Resonant frequency	f_r	141.54kHz

Fig. 7 (a) shows the resonant tank current I_r and the inverter midpoint voltage U_{in}. It can be seen that the resonant current lags the midpoint voltage, which provides convenience for the achievement of zero-voltage switching of MOSFETs. Fig. 7 (b) shows U_{gs} and U_{ds} of MOSFET Q_1. Obviously, the zero voltage switching is achieved.

Fig.8 is the transient response of this system with a step input, which shows that this system is stable after 100 μs with little overshoot.



(a) I_r and U_{in} (b) U_{ds} and U_{gs}

Fig.7. Waveforms of the TETS

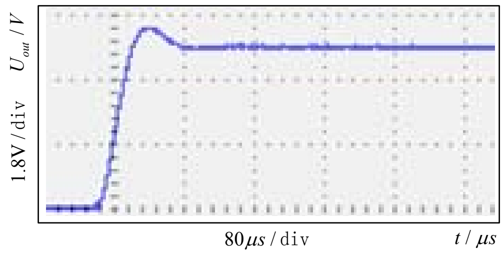


Fig.8. Transient response of LLC resonant TETS

Table 2 lists experimental results of output voltage at different distance in this system. According to these data, the proposed system can transmit energy steadily to secondary side and the output voltage can be regulated with little fluctuation. When distance between transformer coils increases, the VF controller changes operating frequency to keep a stable output voltage.

Table 2. Output voltage of the prototype circuit

Distance(mm)	Frequency(kHz)	Output voltage(V)
2mm	182	4.21
3mm	175	4.18
4mm	174	4.23

Fig.9 shows the proposed TETS's efficiency, and the maximum efficiency is 91% at the rated load. With the load becoming light, the efficiency drops, and the efficiency is 65% when load is 30 Ohm.

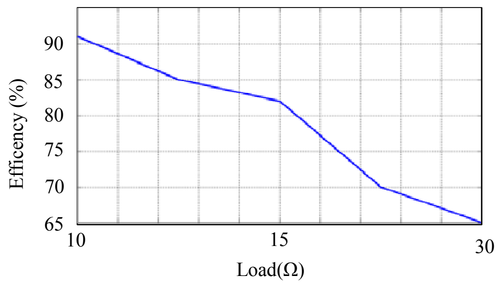


Fig.9. Efficiency of the proposed TETS

Conclusions

In this paper, the theoretical analysis and design considerations of the TETS based on LLC resonant converter are proposed. The characteristics and advantages of the converter are explained. In addition, the equivalent circuit and operational principle are derived to analyze the LLC resonant converter. For this converter the leakage inductance and magnetizing inductance are used for resonant devices in order reduce circuit size. Compared to the traditional capacitor- compensated resonant tank, the proposed system is more suitable for the implanted biological instruments with a small circuit volume. Furthermore, the experimental results obtained from a prototype show the validated advantages of this TETS based on LLC resonant converter.

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