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Frequency Tracking of Resonance Frequency Variation of L-C Circuits for Wireless Energy Transmission to Medical Devices in Human Organs

Yoon-Myoung Gimm[1,2] · Young-Jun Ju[1] · Yu-Ri Lee[1] · Dong-Yeol Lee[1] · Jong-Wook Wang[2]

Abstract

A capsular endoscope (CE) for inspection of the large intestine requires a motor for backward navigation against the autonomous travel in the intestine. This study proposes an HF power system for generating a magnetic field and for delivering wireless power to the internal or implanted medical devices. The magnetic field is generated by a wound coil (L) around a wooden frame, and the current is driven to the coil through a resonating capacitor (C). The characteristics of the resonance frequency shifting of the L-C series circuit are analyzed.

A stable magnetic field intensity in the field coil is maintained by a specially designed frequency tracking system that automatically follows the L-C resonance frequency. Testing confirmed that the oscillation system tracks well the parameter changes of the electric components caused by the operating conditions or environmental variations.

Key words: Wireless Power Transmission, L-C Resonance, Frequency Tracking Oscillator, Magnetic Field Generator.

Ⅰ. Introduction

The conventional endoscope is a very effective medical tool for viewing the internal digestive organizations of the human body. The relative geometrical structure of the endoscope and the small intestine, however, limits the extent of inspection any further than the stomach.

Nowadays, capsular endoscopes (CEs) are preferred for the evaluation of obscure gastrointestinal bleeding because they can overcome the difficulty of using conventional tethered endoscopy to access areas like the small bowel [1]. In addition, a CE that moves from the anal region to the deep areas of the large intestines can be developed, thereby replacing the conventional endoscope for large intestine examination.

The present limitation of the CE is insufficient battery capacity. If conventional batteries are used in a CE, the batteries can potentially be completely discharged before passing through the colon from the anus to the small intestine by powered motion. Because of the limited volume of the CE, enlarging the battery is almost impossible. For this reason, inductive coupling technology has been studied as one of the alternative methods for delivering the continuous power to CEs.

A magnetic field in the frequency below 1 MHz has very low loss inside human body [2], [3]. Energy is efficiently driven from outside to the capsule inside the body by generating a magnetic field with a L-C resonant circuit.

However, the values of L and C are not constant; they change continuously in response to the outside parameters of L or by the inside parameters of C during operation. Therefore, the resonance frequency constantly varies once operation begins, and this causes continuous changes in the driving current. For proper and stable power delivery, the driving frequency should follow the changes in the L-C values.

Fu et al. detected the driving AC current variation and controlled a phase-locked loop and PWM driver for a 3 cm distance power delivery from the transmitting coil to the receiving coil [4]. Our scheme is detects current and voltage waveforms of the load coil and compares the phase between them in order to follow the real load impedance at the resonance condition.

Ⅱ. Power Transmission by Inductive Coupling

Fig. 1 shows the wireless power transmission with inductive coupling. The coil is made by winding wire onto the patient's jacket, so the inductance of the field-generating coil fluctuates constantly. The signal source shown in Fig. 1 generates a sinusoidal waveform and drives a high power amplifier, which supplies sufficient current to the magnetic field generating coil. Because the coil has a high positive reactance, a capacitor is usually connected to compensate the positive reactance [5].

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[1]Department of Electronics and Electrical Engineering, Dankook University, Youngin, Korea.
[2]EMF Safety Inc.
Corresponding Author : Yoon-Myoung Gimm (e-mail : gimm@dku.edu)

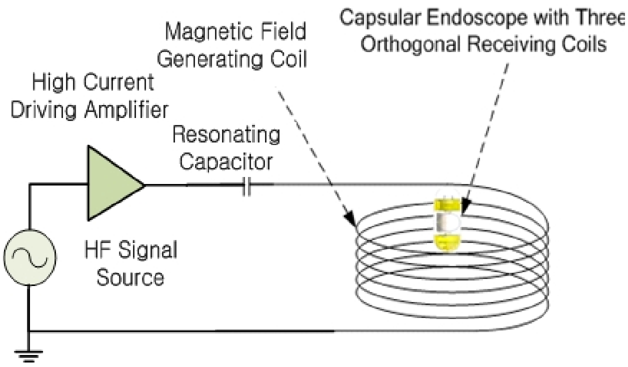

Fig. 1. Wireless power transmission system by inductive coupling.

The current through the coil generates the magnetic field (~ 100 A/m) inside the coil for wireless power transmission to the CE [6].

The magnetic flux penetrates linkage coils in the CE and generates the induced emf (electromotive force). The emf is rectified and regulated, and it operates the entire CE system.

Fig. 2 shows the structure of the magnetic field coil for the inductive coupling test. The coil structure is made by rectangular windings on a wooden frame with dimensions of 450 mm (width) × 250 mm (depth) × 450 mm (height) with 20 turns. Magnetic field H measured by Wandel & Goltermann EMR-300 above the central position of the coil frame is about 100 A/m (rms) when the coil current is 2.6 A (rms).

The electrical system for magnetic field generation is shown in Fig. 3. It consists of a signal source, a source resistance, a resonating serial capacitor, and a magnetic field generating coil. R_{coil} and L can be varied by the environmental conditions of the coil.

Fig. 2. Magnetic field generating coil wound on a wooden frame. A small resonating capacitor for L-C series resonance is hidden and not shown in the figure.

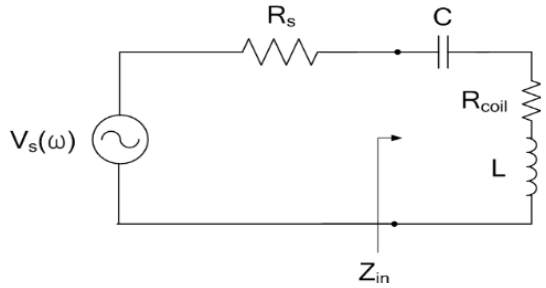

Fig. 3. Current driving circuit for magnetic field generation.

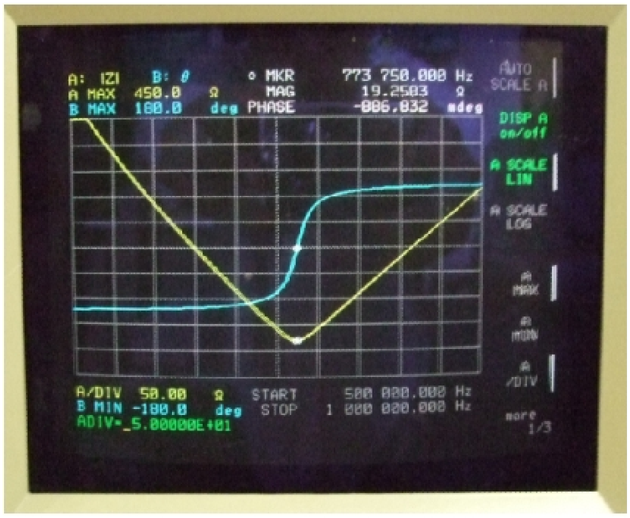

Fig. 4. Magnitude and phase characteristic of L-C resonating circuit in Fig. 3 without any material in the coil depicted in Fig. 2. The V-shape is the magnitude curve and the step-shape is the phase angle of the complex impedance in the 500 ~ 1,000 kHz band.

The capacitance C in Fig. 3 for the serial resonance is 355 pF and the inductance L of the coil is 118 μH at 800 kHz, as measured by a HP 4192A Impedance Analyzer.

The capacitor and the coil are serially resonated at 777 kHz. The measured resonance frequency with empty space inside the coil volume is 774 kHz, as shown in Fig. 4, as measured by a HP 4194A Impedance/Gain-phase Analyzer.

When both hands of a person are put inside the coil volume, the resonating frequency moves down to a lower frequency of 765 kHz, as shown in Fig. 5. The reason for this down-shift of the resonance frequency could be that the inductance L in Fig. 3 is increased slightly with the resistive conductors (hands) in the coil.

The resonating frequency also moves up to a higher frequency as the current flow through the coil increases

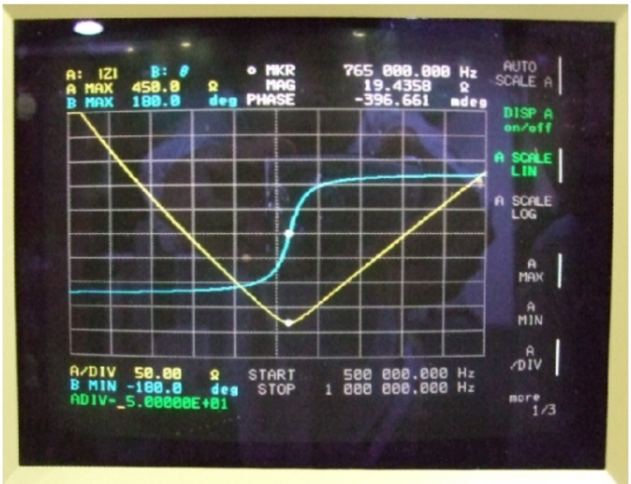

Fig. 5. Magnitude and phase characteristic of L-C resonating circuit with two hands in the coil volume in Fig. 2. The V-shape is the magnitude curve and the step-shape is the phase angle of the complex impedance.

for a higher magnetic field.

The explanation could be that the separation distance between the two conducting sheets of the resonating capacitor C increases due to the raised temperature of the insulating dielectric materials that are heated up by the increased electric current flow, which then induces the decreased capacitance of the resonating capacitor C. Alternatively, the explanation might involve the temperature dependent characteristics of the dielectric constant of the insulating material between the capacitor plates. A third explanation might concern the nonlinear characteristics of the dielectric constant of the insulating material of the resonating capacitor when the electric field is sufficiently large in the capacitor. As the E-field in the capacitor becomes larger, the dielectric constants becomes smaller due to the saturation of the polarization.

The circuit in Fig. 3 is operated by a high voltage source to generate a 10 A/m magnetic field intensity at the near-central position of the coil volume in Fig. 2 at the resonant frequency.

The magnetic field intensity (H) varies in Fig. 6 as the operating frequency of the source in Fig. 3 changes from 764 to 790 kHz, which shows the resonance characteristics. In this case, the capacitor is heated up and the resonance frequency moves up to 780 kHz from 774 kHz, as shown in Fig. 4 where no hands are inside in the coil volume.

The frequency characteristics of the generated magnetic field intensity when two hands are in the coil are shown by the red curve with the square dots in Fig. 6. The resonance frequency is up-shifted from 765 kHz in Fig. 5 to 774 kHz in Fig. 6 with a small magnetic field attenuation.

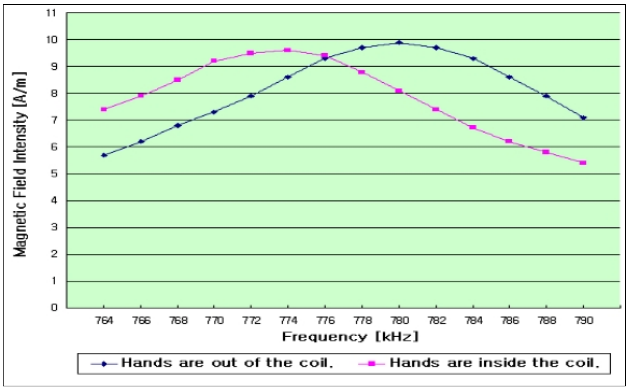

Fig. 6. Magnetic field intensity variation in the coil structure of Fig. 2 by sweeping the driving frequency of the source in Fig. 3 (manual mode). The blue curve marked by diamonds shows the magnetic field without hands in the coil; the red curve marked by squares shows the field with hands in the coil.

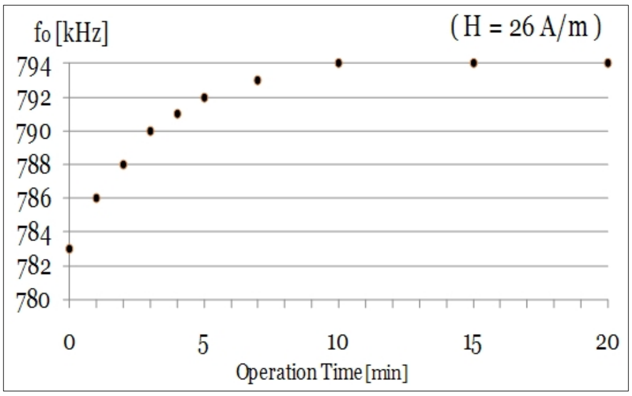

Fig. 7. Maximum field frequency (resonance frequency) variation with operation time.

Fig. 7 also shows that resonance frequency changes with operation time. When the hands are outside of the coil and the field intensity is increased to 26 A/m for a quick time-variation, the measured resonance frequency is 783 kHz at the initial operation time. The resonance frequency is saturated at 794 kHz after 10 minutes.

All of these variations of the resonance frequency need a tracking source for the variable L-C resonance frequency.

Ⅲ. Resonance Frequency Generator

The block diagram of the oscillator that traces the L-C resonating frequency is shown in Fig. 8.

The signal is generated by a VCO(Voltage Controlled Oscillator) and amplified, and the current and voltage waveforms are picked up by the transformer sensors.

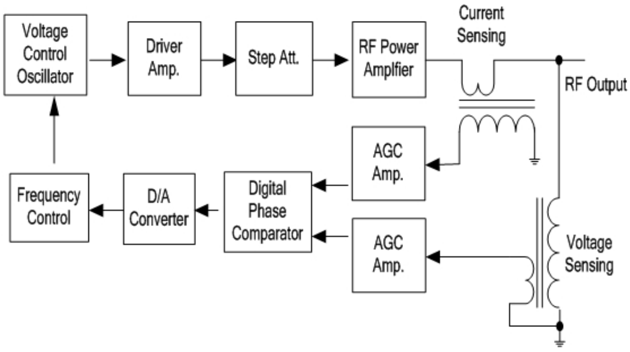

Fig. 8. Block diagram of the resonance tracking HF generator.

As seen in Fig. 4 and 5, the resonance occurs when the phase angle of the impedance is 0°. The phase between the voltage and current waveforms can be matched by the feedback mechanism if the driving frequency is at resonance.

The rf output current and voltage are sensed by the sensing transformers in Fig. 8. To compare the two waveforms properly, the two waveforms should have approximately the same amplitude, and the AGC amplifiers perform that role.

The digital phase comparator measures the phase difference between the voltage and current waveforms, which determines if the load is capacitive or inductive. If the load impedance Z_{in} in Fig. 8 is inductive, the VCO should generate a lower frequency, and if the load is capacitive, the VCO should generate higher frequency. By doing these actions repeatedly, the system attempts to approach the pure resistive Z_{in}, which means that the system is in a resonating condition.

This feedback mechanism ensures that the L-C circuit is always in a resonant state, independent of the load input impedance Z_{in} or variations of L and C parameters shown in Fig. 3.

Using the resonance-tracking generator in Fig. 8, the circuit in Fig. 3 was operated again to check how well the generator tracks the resonance frequency.

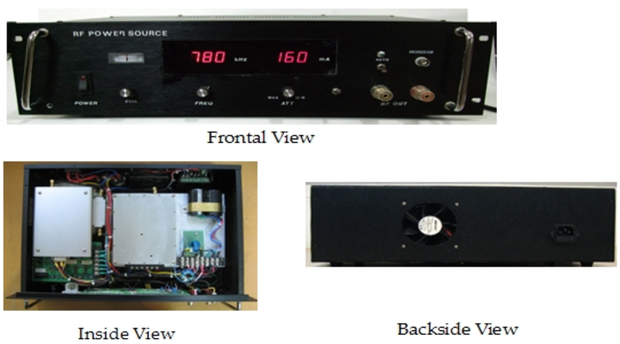

Fig. 9. Prototype of the frequency tracking generator.

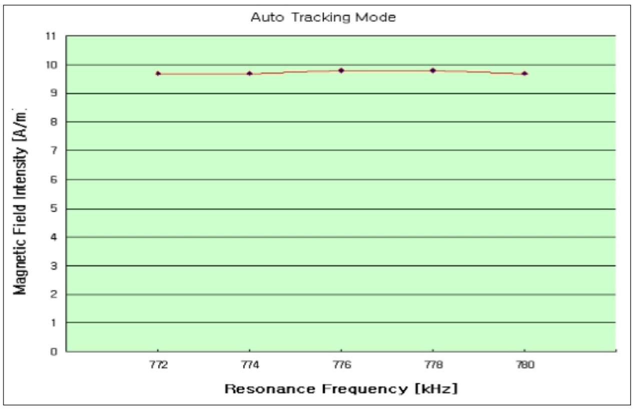

Fig. 10. Resonance frequency and magnetic field intensity at the resonance while adjusting the depth of the position of the two hands in the coil in Fig. 2. The resonance frequency automatically follows the changed environment by the feedback circuit in Fig. 8 (auto tracking mode).

Fig. 9 shows the exterior and interior views of the developed frequency-tracking generator.

If hands are out of the coil structure of Fig. 2, the generator automatically locked to 780 kHz, producing 9.7 A/m, as shown in Fig. 10. When the two hands were moved to the central wooden board plate shown in Fig. 2 and the two palms touched with the plate, the resonance frequency moved down to 772 kHz. The magnetic field intensities remained in a range between 9.6 A/m~9.8 A/m range throughout the resonance frequency range, which seemed a reliable HF magnetic field source against the changing environments surrounding the wound coil.

The response time of the feedback system is measured by an additional capacitor C_{add} (30 pF) placed in parallel connection with the original capacitor C (355 pF), as indicated in Fig. 11. The manual on/off switching action of the switch and the output voltage frequency on the analog CRO confirmed that the response was too quick to measure by watching the period change of the waveform on the CRO screen using human eyes alone. If a reading of the delay time is neces-

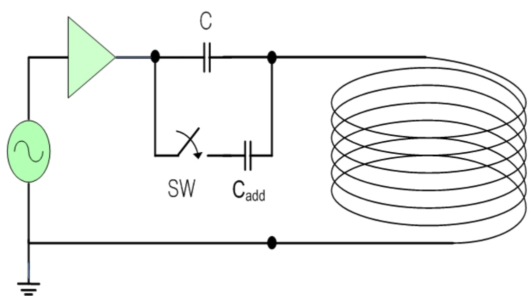

Fig. 11. Response time measurement system.

sary, an additional electronic time-delay measurement system can be devised.

The tracking generator was confirmed to cover the resonant frequency range of 400～900 MHz. The magnetic field intensity can be varied from 3 to 130 A/m, and the harmonic current is less than －30 dBc.

Ⅳ. Conclusion

In this paper, an auto-tracking high frequency current source was developed for generating a constant magnetic field intensity against changing environmental conditions. This generator makes possible the wireless transmission of power continuously to a capsular endoscope. The oscillation frequency follows the variation of any parameter changes of the L-C resonating circuit.

Without this tracking oscillator, the magnetic field generating system is unstable because the resonating frequency sways up to some tens of kHz by the operation duration time or by the condition of material inside the field generating coil, or by the magnetic field intensity to be obtained.

By controlling the VCO frequency, after comparing the phase angle difference of the voltage and current waveforms of the field generating coil, the feedback network can be used to track the resonating frequency of the L-C series circuit.

The development of this auto-tracking oscillator makes it possible to obtain stable DC power from a capsular endoscope positioned inside of the field-generating coil.

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Yoon-Myoung Gimm

received the B.E. degree in electronics engineering from the Seoul National University, Seoul, Korea, in 1975, and the M.S. and Ph.D. degrees in electrical and electronics engineering from Korea Advanced Institute of Science and Technology (KAIST) in 1977 and 1990, respectively. Since 1980, he has been in the department of electronics engineering, Dankook University, where he is now a professor in the school of electronics and electrical engineering. He is also a CEO of EMF Safety Inc. since 2000. His research interests are the electromagnetic field measurements related with the biological effect and human safety.

Young-Jun Ju

received the B.E. and M.S. degrees in electronics and electrical engineering from Dankook University in 2002 and 2004, respectively. He is currently a Ph. D. candidate electronics and electrical engineering, Graduate School, Dankook University, Yongin, Korea. His research interests are the electromagnetic field measurements related with the human safety and wireless power transfer.

Yu-Ri Lee

received the B.E. degree in electronics and electrical engineering from Dankook University in 2009. She is currently a M. S. candidate in electronics and electrical engineering, Graduate School, Dankook University, Yongin, Korea. Her research interests are the electromagnetic field measurements related with the human safety and wireless power transfer.

Dong-Yeol Lee

received the B.E. degree in electronics and electrical engineering from Dankook University in 2009. He is currently a M. S. candidate in electronics and electrical engineering, Graduate School, Dankook University, Yongin, Korea. His research interests are the electromagnetic field measurements related with the human safety and wireless power transfer.

Jong-Wook Wang

received the B.E. degree in computer engineering from Korean Educational Development Institute in 2005. He received the M.E. degree in electronics and electrical engineering from Dankook University in 2008, and now he is working in the EMF Safety Inc.. His research interests are the electromagnetic field measurement instruments development.