LETTER

Time-Division Multiplex Auto-Impedance Matching System for High-Intensity Focused Ultrasound

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Abstract High-intensity focused ultrasound (HIFU) has been confirmed to be useful for cancer therapy. However, the miniaturization of traditional impedance matching networks for HIFU has limitations. In this paper, a time-division multiplex auto-impedance matching network is proposed for Class D power amplifiers used in HIFU systems to improve performance and reduce the system size. A comparison with previous articles shows that the proposed system can automatically compensate for the impedance drift caused by temperature variations or manufacture tolerance. The operating frequency of the circuit is 1.25 MHz, and the power consumption is 416 mW.

Keywords: High-Intensity Focused Ultrasound, Time-division Multiplex, Automatic Impedance matching

Classification: Devices, circuits and hardware for IoT and biomedical applications.

1. Introduction

Recent studies on high-intensity focused ultrasound (HIFU) have shown great promise for cancer therapy. In a HIFU system, a designed transducer array is utilized to focus a beam of ultrasound (100 kHz ~ 10 MHz) energy into small volumes of tissue inside human organs. The focused beam causes localized heating (45~90\(^\circ\)C) in a small region, and the target tissues are ablated without the need for an incision [1, 2, 5, 4, 5]. Since magnetic resonance imaging (MRI) can provide real-time, noninvasive temperature measurement and 3D imaging with excellent contrast, the combination of MRI and HIFU has proven to be very useful in the mediated drug delivery [6, 7], and noninvasive functional neurosurgery [8, 9, 10].

For a HIFU system to operate optimally, its power supply must be carefully designed to generate enough ultrasonic energy into the human body. Power amplification is usually achieved by a Class D or Class DE power amplifier because of its high-power efficiency [11, 12, 13, 14]. Most ultrasonic transducers can be considered complex impedance components. Furthermore, the output impedance of the Class D or Class DE amplifier is resistive. Therefore, a matching network must be applied between the amplifier and the transducer. Otherwise, there will be reflected power, which will cause a temperature rise or even unrecoverable damage to the transducer. Static impedance matching network presented in [15, 16, 17] can solve this problem. However, during HIFU surgery, the impedance of the transducers has unavoidable variations that are caused by temperature drifting, aging and manufacturing dispersion, which will produce unpredictable results of the HIFU system.

A traditional solution is to use automatic resonance frequency tracking method [18, 19, 20] or variable components such as controllable capacitors, controllable inductors or varactors to solve the impedance matching and drifting problems [21, 22, 23]. However, for the methods presented in [18, 19, 20], the frequency of power signal applied on the transducer is changed by using automatic resonance frequency tracking system, which is not acceptable in a HIFU system. [21, 22, 23] use controllable components instead of frequency tracking method to solve the problem. But, these methods only focus on the impedance variation caused by manufacturing tolerance, and the impedance variations caused by temperature drifts during the HIFU surgery are not considered. In other words, these methods are not suit for the dynamic impedance matching during HIFU surgery. Moreover, the impedances of the transducers in the phased array need to be measured, and all of them require computer to store the measured impedances and calculate the switch control signal. Therefore, system size and power consumption will also limit these solutions.

In our previous study, a novel auto-tuning network based on a special phase locking loop (PLL) structure that use a zero-voltage switched (ZVS) capacitor to compensate the impedance drifting during the working period of wireless power transmission applications [24]. Another preliminary test confirmed that this circuit is also suitable for the dynamic impedance matching of HIFU system [25]. However, it can only be used for one-channel transducers, and the circuit size is still not sufficient for phased-array HIFU. Since, the time-division multiplex (TDM) technology has been used in many circuits to minimize the circuit size and reduce system complexity [26, 27, 28, 29]. In this paper,

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a time-division multiplex auto-impedance matching circuit is proposed. By reusing the proposed auto-matching circuit, we can reduce additional hardware and area overhead.

2. Impedance matching analysis

The transducer used in the HIFU system consists of four parts: piezoelectric active element, transducer casing, backing layer, and coaxial cable. The ultrasound signal is generated by a piezoelectric active element in the transducer. The modeling of the ultrasonic transducer can be simplified to model the piezoelectric active element, which can be considered an electromechanical vibration system. A well-known equivalent model of the piezoelectric transducer [30] based on electrical and mechanical characteristics is depicted in Fig. 1 (a).

This model is composed of a static branch and a motional branch. \( R_P \) and \( C_P \) represent the static electrical characteristics of the piezoelectric transducer, and \( L_M, C_M \). \( R_M \) represent its mechanical characteristics. \( R_P \) is neglected because of its very large value. The equivalent electrical impedance of the transducer \( Z \) can be obtained by,

\[
Z = R + Xj
\]

where the resistance \( R \) and the reactance \( X \) of the transducer can be expressed as,

\[
R = \frac{R_M}{w^2C_P^2R_M^2 + \left[1-wC_P\left(wL_M - \frac{1}{wC_M}\right)\right]^2}
\]

\[
X = \frac{wL_M - \frac{1}{wC_M} - wC_P\left[R_M^2 + \left(wL_M - \frac{1}{wC_M}\right)^2\right]}{w^2C_P^2R_M^2 + \left[1-wC_P\left(wL_M - \frac{1}{wC_M}\right)\right]^2}
\]

Fig. 2 presents the impedances of 256 transducers used in this study, working at their resonance frequency of 1.25 MHz. \( R \) and \( X \) define the resistance and the reactance of the impedances, respectively.

These impedances are measured at different temperatures by using a vector network analyzer (DG8SAQ VNWA 3E). The short-open-load-thru (SOLT) calibration method is used here to remove the parasitic effects introduced by the bayonet nut connectors. As seen in this figure, although the 256 elements are composed of the same piezoelectric material and have the same shape (6 mm diameter), impedance dispersions are noticeable.

Table I shows the impedance characteristics of the 256 transducers. The variations in the resistance and the reactance caused by manufacturing tolerances combined with temperature drifting is

\[
\begin{array}{|c|c|c|c|c|}
\hline
T=25.0^\circ C & \text{Minimum} & \text{Maximum} & \text{Average} & \text{Std} \\
\hline
R & 17.38 \ \Omega & 48.33 \ \Omega & 31.83 \ \Omega & 6.21 \\
X & -361.08 \ \Omega & -197.10 \ \Omega & -293.33 \ \Omega & 25.91 \\
\hline
T=32.5^\circ C & \text{Minimum} & \text{Maximum} & \text{Average} & \text{Std} \\
\hline
R & 17.38 \ \Omega & 48.33 \ \Omega & 31.83 \ \Omega & 6.21 \\
X & -361.08 \ \Omega & -197.10 \ \Omega & -293.33 \ \Omega & 25.91 \\
\hline
T=40.0^\circ C & \text{Minimum} & \text{Maximum} & \text{Average} & \text{Std} \\
\hline
R & 17.38 \ \Omega & 48.33 \ \Omega & 31.83 \ \Omega & 6.21 \\
X & -361.08 \ \Omega & -197.10 \ \Omega & -293.33 \ \Omega & 25.91 \\
\hline
T=47.5^\circ C & \text{Minimum} & \text{Maximum} & \text{Average} & \text{Std} \\
\hline
R & 17.38 \ \Omega & 48.33 \ \Omega & 31.83 \ \Omega & 6.21 \\
X & -361.08 \ \Omega & -197.10 \ \Omega & -293.33 \ \Omega & 25.91 \\
\hline
T=55.0^\circ C & \text{Minimum} & \text{Maximum} & \text{Average} & \text{Std} \\
\hline
R & 17.38 \ \Omega & 48.33 \ \Omega & 31.83 \ \Omega & 6.21 \\
X & -361.08 \ \Omega & -197.10 \ \Omega & -293.33 \ \Omega & 25.91 \\
\hline
\end{array}
\]

The diagram and simplified circuit of auto-impedance matching system based on synchronous switched capacitor presented in our previous study [24] are shown in Figure 3.

The reactance of the inductor \( L \) and the susceptance of the equivalent capacitor \( C_{eq} \) that represents \( C_S \) and \( C_{fix} \) in the variable \( L \)-type tuning network are defined as \( X_L \) and \( B_{C_{eq}} \), respectively. \( Z_0 \) represents the output impedance of the power supply.
Fig. 3 Diagram and simplified circuit of the one-channel impedance matching system [24].

To ensure that the impedance of the transducer is well matched to the power supply, the following equation must be true.

\[ Z_0 = jX_L + \frac{1}{jB_{CEq} + 1/(R + X)} \]  

(4)

As known previously, \( Z_0 \) is purely resistive. Then, we can obtain the following simultaneous equations:

\[
\begin{align*}
B_{CEq} (X_L R - XZ_0) &= R - Z_0 \\
X_L (1 - B_{CEq} X) &= B_{CEq} R - X
\end{align*}
\]  

(5)

The impedance compensation range of the auto-impedance matching network is required to cover the impedance variations caused by manufacturing tolerances and temperature drifting. In our former paper, in order to achieve a linear transfer function, the inductor \( L \) in the L-type matching network is set to be constant, and \( X_L \) can be calculated by introducing the average value of \( R \) and \( X \) into Eq. (5). Then, the range of the values of \( B_{CEq} \) can be obtained.

\[
\frac{R_{\text{min}} - Z_0}{R_{\text{max}} X_L + Z_0 X_{\text{max}}} \leq B_{CEq} \leq \frac{R_{\text{max}} - Z_0}{R_{\text{max}} X_L - Z_0 X_{\text{min}}}
\]  

(6)

where \( R_{\text{max}}, R_{\text{min}}, R_{\text{avg}} \) represent the maximum, minimum and mean values of the resistance, respectively, with temperature ranging from 25°C to 55 °C. \( X_{\text{max}}, X_{\text{min}}, X_{\text{avg}} \) define the maximum, minimum and mean values of the reactance, respectively.

According to the principle of switched capacitor, the range of the values of \( B_{CEq} \) can also be expressed as,

\[
w \left[ \frac{C_{\text{eq}}}{C_{\text{eq}}} + \text{Min}(C_{\text{eq}}) \right] \leq B_{CEq} \leq w \left[ C_{\text{eq}} + \text{Max}(C_{\text{eq}}) \right]
\]  

(7)

where \( C_{\text{eq}} \) defines the equivalent capacitance of \( C_s \), \( \text{Max}(C_{\text{eq}}) = C_s \), and \( \text{Min}(C_{\text{eq}}) = 0 \). \( C_{\text{eq}} \) and \( C_s \) can be calculated by solving Eqs. (6) and (7). For this study, \( Z_0 = 0.04 \Omega \), and the values of \( R_{\text{mean}}, R_{\text{max}}, R_{\text{min}}, X_{\text{mean}}, X_{\text{max}} \) and \( X_{\text{min}} \) are illustrated in Table I. Therefore, \( L = 1.33 \mu H, C_{\text{Fix}} = 11.64 \text{nF}, \) and \( C_s = 184.91 \text{pF} \).

Fig. 4 Diagram of the proposed time-division multiplex auto-impedance matching system.
3. Time-Division Multiplex Auto-Impedance Matching System

The diagram of the proposed time-division multiplex auto-impedance matching system based on our previous study is shown in Fig. 4. It consists of three parts: five-channel transducers, a digital control circuit, and a feedback loop.

The feedback loop is achieved by using the circuit presented in [25]. The digital control circuit consists of a microcontroller unit (MCU) and a ten-channel analog switch. The control signal of the analog switch is generated with the MCU. Fig. 5 illustrates flow chart of the proposed time-division multiplex auto-impedance matching system. The system has five working periods, and the core flows of the different periods are basically the same. Therefore, intermediate steps were omitted.

In period Channel 1, \( V_{PA} \) and \( V_{CFix} \) of the first channel are connected to the feedback loop. The first channel of the system is working in auto-impedance matching mode. The other channels are working as power amplifiers with static impedance matching networks. Switching control signal \( V_{PWM} \) output from port O1 of the MCU. Then, MCU starts to check the status of the switching control signal \( V_{PWM} \). If \( V_{PWM} \) is stable, it is stored and continuously outputted at port O1, and the next period started. If \( V_{PWM} \) is unstable, then a check is performed on whether the operation time of period Channel 1 \( T_{Per1} \) exceeds the preset time \( T_{Preset} \). If the operation time of period Channel 1 exceeds \( T_{Preset} \), period Channel 1 is ended, and the next period is started; otherwise the status of \( V_{PWM} \) is checked again. The settling time of the auto-matching network is less than 15 periods with a working frequency of 1.25 MHz in the worst case. To ensure the stability of the system, the preset time \( T_{Preset} \) is required to be greater than or equal to the settling time of the auto-matching network. Thus, in this paper, \( T_{Preset} \) is set to 15 periods.

4. Test Results

Fig. 6 shows the equivalent impedances of 256 transducers using impedance matching methods presented in [17], [23] and this paper, respectively. \( Im(Z) \) presents the imaginary part of the impedance, and \( Re(Z) \) is the real part of the impedance. The output impedance of the class D amplifier used in this work is 0.04 \( \Omega \). Table II gives out the impedance characteristics of 256 transducers with different matching methods.

As can be known from the test results, the method proposed in [17] is unable to compensate the variations of the impedances caused by the temperature variations as well as the manufacturing tolerance.
However, the imaginary impedance variations mainly caused by temperature is not compensated. For our method presented in this paper, the impedance variations caused by the temperature variations and the manufacturing tolerance are well compensated.

Table II. Impedance Characteristics of 256 Transducers with Different Matching Methods.

| Parameters | [17] | [23] | This work |
|------------|------|------|-----------|
| $T=25.0^\circ C$ | \begin{align*} \text{avg}(Z) & = 0.040-0.002i \Omega \\ \text{std}(Z) & = 0.0346 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.039-0.008i \Omega \\ \text{std}(Z) & = 0.0050 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.039-0.0002i \Omega \\ \text{std}(Z) & = 0.0044 \end{align*} |
| $T=32.5^\circ C$ | \begin{align*} \text{avg}(Z) & = 0.041+0.011i \Omega \\ \text{std}(Z) & = 0.0357 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.040+0.004i \Omega \\ \text{std}(Z) & = 0.0063 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.041-0.0004i \Omega \\ \text{std}(Z) & = 0.0045 \end{align*} |
| $T=40.0^\circ C$ | \begin{align*} \text{avg}(Z) & = 0.043+0.031i \Omega \\ \text{std}(Z) & = 0.0377 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.042+0.024i \Omega \\ \text{std}(Z) & = 0.0063 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.043+0.0002i \Omega \\ \text{std}(Z) & = 0.0045 \end{align*} |
| $T=47.5^\circ C$ | \begin{align*} \text{avg}(Z) & = 0.046+0.053i \Omega \\ \text{std}(Z) & = 0.0398 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.044+0.046i \Omega \\ \text{std}(Z) & = 0.0091 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.046-0.0001i \Omega \\ \text{std}(Z) & = 0.0050 \end{align*} |
| $T=55.0^\circ C$ | \begin{align*} \text{avg}(Z) & = 0.047+0.072i \Omega \\ \text{std}(Z) & = 0.0421 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.046+0.065i \Omega \\ \text{std}(Z) & = 0.0118 \end{align*} | \begin{align*} \text{avg}(Z) & = 0.048-0.0002i \Omega \\ \text{std}(Z) & = 0.0050 \end{align*} |

Power efficiencies of the amplifiers with different matching networks are shown in Fig. 7. The maximum power efficiency of the class D amplifier used in this paper is 91.2%. Fig. 7 (a) presents the test results by using the matching system proposed in [17]. Fig. 7 (b) gives out the results by using the matching method presented in [23]. The results of the matching system in this paper is illustrated in Fig. 7 (c).

Table III. Comparison between different references and this study.

| References | [17] | [23] | This work |
|------------|------|------|-----------|
| Working frequency | 125kHz | 1.5MHz | 1.25MHz |
| Average efficiency | 49.9% | 61.9% | 82.5% |
| Standard deviation | 0.26 | 0.25 | 0.06 |
| Minimum efficiency | 4.7% | 14.4% | 45.8% |
| Support channels | 1 | 1 | 5 |

Fig. 8 shows the prototype of the five-channel time-division multiplex auto impedance matching system. The feedback network has been implemented and the time-division multiplex circuit has been achieved by using PCB with a size of 5 cm × 10 cm.

5. Conclusion

In this paper, a time-division multiplex auto impedance matching system is proposed for the class D power amplifiers used in the HIFU system. Different from the
for HIFU therapy." IEEE transactions on biomedical circuits and systems 10.2 (2016): 375-382 (DOI: 10.1109/TBCAS.2015.2406119).

[15] Huang, Haiying, and Daniel Paramo. "Broadband electrical impedance matching for piezoelectric ultrasound transducers." IEEE transactions on ultrasonics, ferroelectrics, and frequency control 58.12 (2011): 2699-2707 (DOI: 10.1109/TUFFC.2011.2132).

[16] Zhang, Hongjie, et al. "Electrical matching of low power piezoelectric ultrasonic transducers for microelectronic bonding." Sensors and Actuators A: Physical 199 (2013): 241-249 (DOI: 10.1016/j.sna.2013.05.028).

[17] An, Jianfei, et al. "Design of a broadband electrical impedance matching network for piezoelectric ultrasonic transducers based on a genetic algorithm." Sensors 14.4 (2014): 6828-6843. (DOI: 10.3390/s140406828).

[18] Zhang, Hongjie, et al. "A new automatic resonance frequency tracking method for piezoelectric ultrasonic transducers used in thermosonic wire bonding." Sensors and Actuators A: Physical 235 (2015): 140-150. (DOI: 10.1016/J.TIE.2015.2500197).

[19] Zhang, Hongjie, et al. "Welding quality evaluation of resistance spot welding using the time-varying inductive reactance signal." Measurement Science and Technology 29.5 (2018): 055601. (DOI: 10.1088/1361-6501/aaa830).

[20] Wang, Fujun, et al. "Design of high-frequency ultrasonic transducers with flexure decoupling flanges for thermosonic bonding." IEEE Transactions on Industrial Electronics 63.4 (2015): 2304-2312. (DOI: 10.1109/TIE.2015.2500197).

[21] Schweitzer, P., et al. "Feedback sine wave driver design for ultrasonic transducers." The European Physical Journal-Applied Physics 47.1 (2009): 12703. (DOI: 10.1051/epjap:2008181).

[22] Chen, Konle, and Dimitrios Peroulis. "Design of adaptive highly efficient GaN power amplifier for octave-bandwidth application and dynamic load modulation." IEEE Transactions on Microwave Theory and Techniques 60.6 (2012): 1829-1839 (DOI: 10.1109/TMTT.2012.2189232).

[23] De Oliveira, P. Lourenco, et al. "Adjustable impedance tuner for ultrasonic phased-array transducer at 1.5 MHz." Electronics Letters 45.17 (2009): 913-914. (DOI: 10.1049/el.2009.0149).

[24] Rodes, Francis, et al. "Optimization of the power transfer through human body with an auto-tuning system using a synchronous switched capacitor." IEEE Transactions on Circuits and Systems II: Express Briefs 62.2 (2015): 129-133. (DOI: 10.1109/TCSII.2014.2385251).

[25] Wang, Xusheng, et al. "Auto-tuning network for phased-array high-intensity focused ultrasound system." Electronics Letters 54.21 (2018): 1202-1204. (DOI: 10.1049/el.2018.5510).

[26] Carpenter, Thomas M., et al. "Time-division multiplexing for cable reduction in ultrasound imaging catheters." 2015 IEEE Biomedical Circuits and Systems Conference (BioCAS). IEEE, 2015 (DOI: 10.1109/BioCAS.2015.7348448).

[27] Choi, Shin Hyuk, and Dong In Kim. "Multi-cell structure backscatter based wireless-powered communication network (WPCN)." IEICE Transactions on Communications 99.8 (2016): 1687-1696 (DOI: 10.1587/transcom.2015CCP0012).

[28] Jiang, Chaoqiang, et al. "Time-division multiplexing wireless power transfer for separately excited DC motor drives." IEEE Transactions on Magnetics 53.11 (2017): 1-5. (DOI: 10.1109/TMAG.2017.2695656).

[29] Mei, Liang, and Peng Guan. "Development of an atmospheric polarization Scheimpflug lidar system based on a time-division multiplexing scheme." Optics letters 42.18 (2017): 3562-3565. (DOI: 10.1364/OL.42.003562).

[30] Adriaens, H. J. M. T. S., Willems L. De Koning, and Reinder Banning. "Modeling piezoelectric actuators." IEEE/ASME transactions on mechatronics 5.4 (2000): 331-341. (DOI: 10.1109/3516.891044).