Instantaneous input electrical power measurements of HITU transducer

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Abstract. HITU (High Intensity Therapeutic Ultrasound) transducers are widely used in therapeutic ultrasound in medicine. The output ultrasonic power of HITU transducer can be measured in number of methods described in IEC 61161 standard [1]. New IEC standards specifically for measurement of HITU equipment are under development. The ultrasound power radiated from a transducer is dependent on applied input electrical voltage and current and consequently power. But, up to now, no standardised method has been developed and adopted for the input electrical power measurements. Hence, a workpackage was carried out for the establishment of such method in the frequency range of 1 to 3 MHz as a part of EURAMET EMRP Era-net plus “External Beam Cancer Therapy” project. Several current shunts were developed and evaluated. Current measurements were also realized with Philips current probe and preamplifier at NPL and Agilent current probe at UME. In this paper, a method for the measurement of instantaneous electrical power delivered to a reactive ultrasound transducer in the required frequency range is explored.

1. Introduction

The work described in this paper is a deliverable in a workpackage of EURAMET EMRP Era-net plus “External Beam Cancer Therapy” project. The aim is to develop and validate a method for the measurement of instantaneous electrical power delivered to a reactive ultrasound transducer in the frequency range 0.5 to 3 MHz with a target accuracy of ±5%.

New IEC standards specifically for measurement of HITU equipment are under development. The ultrasound power radiated from a source (transducer) is directly dependent on applied electrical voltage and current and consequently power. No method up to now has been developed and adopted for the input electrical power measurements of HITU transducers. HITU transducers are produced to work at discrete resonance frequencies e.g. at 1 MHz or 3 MHz etc. They are typically PZT type transducers a bowl shape and a single focal point. They produce ultrasonic power in water when an oscillating electrical voltage is applied at the correct frequency.

Accurate electrical power measurement is well established in low frequencies applications. When the frequency of interest is higher than 100 kHz, measurement of voltage, current and impedance are easily affected by the input impedance of the measurement equipments. Input impedance of the measurement equipment and the impedance of the transducer contain resistive, capacitive and inductive components and these components change significantly with frequency. Input voltage can be measured in number of ways such as calibrated scope (at the end of cable), rf voltmeter and TVC (thermal...
voltage converter) methods [2]. Input impedance of the measurement equipment is usually close to 50 Ω or 1 MΩ. If the transducer is purely resistive, only straightforward numerical corrections are necessary for between the input impedance of the measurement device and output impedance of the transducer. When the input impedance of the measurement equipment contains reactive components, it should be calculated and whether it should be taken account or not in the phase calculation.

In order to measure the current, two approaches were explored:

i) to design a current shunt

ii) to use a current probe.

2. Current shunts

Four terminal and two terminal current shunts were developed for current measurements at 1 MHz and 3 MHz frequencies (Figure 1). In order to avoid phase error observed in the shunts, compensation circuits were developed. Current, voltage and phase between them were determined. To minimise the effect of inserting a current shunt into the circuit between a power amplifier and transducer, the target impedance of the shunt was 0.1 ohm: this being one percent of the impedance of a transducer with a 10 ohm input impedance. At this level, changes in contact resistance (for instance using a BNC connector) becomes significant.

For three different shunts, time delay between current and voltages were observed. Within the restrictions of this particular project, we were not able to achieve adequate performance of a 0.1 ohm current shunt. There were more promising indications from a 0.25 ohm shunt, however this would introduce a 2.5% voltage drop when measuring a 10 ohm transducer, so we have not pursued this option further at this stage. However, some important observations were made relating to the significance of harmonic distortion in the drive signal. Harmonics produce power half cycles of different amplitude and shape, and a reactive load impedance results in each power half cycle itself being asymmetric. In practice, the output of many HITU amplifiers will be distorted: whilst this usually only has a small effect on the acoustic output power, it can introduce large errors when measuring electrical power if the amplitude of the voltage or current is used to calculate power.

2. Current probes

Current measurements were realized at NPL with Philips current probe and preamplifier and at UME with Agilent 1147A current probe. The results presented here relate to the work at UME. The power measurement set-up is shown in Figure 2. The output of the power amplifier is directly connected to the magnetic coupled current probe. The ultrasonic transducer with cable is connected to the one port.
of Tee BNC which is the definition point for all electrical measurements, the other port of the Tee BNC is employed for the voltage measurements. The voltage measurement feature of the scope was calibrated by an RF Voltmeter and the correction factor of the scope voltage measurements determined. Agilent 4294A is used for the two terminal impedance measurements. The reference point for the two terminal impedance measurement is one port of the Tee BNC. The calibration of the impedance analyzer was realized at this point.

Devices used in the set up:
- Generator : Agilent 33250A
- Power Amplifier : ENI (150 W) and E&I (500 W)
- Infinium Scope : Agilent 500 MHz, 2GSa/s
- Current Probe : Agilent 1147A compatible with Agilent scope
- Impedance Analyzer : Agilent 4294A
- HITU transducer : Precision Acoustics and Sonic Concepts H-102
- RF Voltmeter : Rohde & Schwarz URE3
- Balance : Mettler Toledo PR2004

All the devices used in the set up were traceable to electrical standards. A 50 Ohm resistive load that was measured with the impedance analyzer used to verify the current probe readings. The current probe was kept heated, demagnetized and levelled before the measurements according to its manual and checked during measurements. The calibration of the impedance analyzer was done at the end of cable. Voltage measurements were realized with both RF voltmeter and the scope which are calibrated by a voltage laboratory.

Current measurements were realized with a calibrated current probe. Impedance and phase were also measured with impedance analyzer. Phase measured between voltage and current are in agreement with the phase measured with impedance analyzer in few degrees (Figure 3 and 4). However, there are sections of the curves which show systematic differences between the methods.

Figure 2. Ultrasound power and input electrical power measurement set-up
3. Measurements

Ultrasound power was measured with absorbing target by conventional methods described in IEC 61161 standard [1]. Input electrical voltage, current and phase between them were measured at the same time using an scope. Impedance and phase had been previously measured with an impedance analyzer in a separate set-up. Input electrical power was calculated with three ways.

Electrical power $P_1$, was calculated by multiplying $rms$ input voltage ($V$), current ($I$) and phase ($\theta$) between them as;

$$P_1 = V \cdot I \cdot \cos(\theta)$$  \hspace{1cm} (1)

Electrical power $P_2$; was calculated by multiplying $rms$ electrical input current and resistance measured with Impedance Analyzer

$$P_2 = I^2 \cdot R$$ \hspace{1cm} (2)

Electrical power $P_3$; was calculated from the $rms$ electrical input voltage and the phase and resistance measured with Impedance Analyzer.

$$P_3 = V \cdot I \cdot \cos(\theta) = V \cdot \frac{V}{Z} \cdot \cos(\theta) = V \cdot \frac{V}{R \cdot \cos(\theta)} \cdot \cos(\theta) = \frac{V^2}{R} \cdot \cos(\theta)^2$$  \hspace{1cm} (3)

Figure 3. Difference between phases measured by scope and impedance analyzer for Sonic Concepts

Figure 4. Difference between phases measured by scope and impedance analyzer for Precision Acoustics
Figure 5. Electrical powers and ultrasound power for Sonic Concepts transducer.

Figure 6. Electrical powers and ultrasound power for Precision Acoustics transducer.
4. Results

Measurement results are shown in Figure 5 and 6. This work shows good correlation between electrical power measurements and direct measurements of the power of the ultrasonic transducers which are immersed into the water. During the measurements, no harmonic distortion was observed in the amplifier output at the defined output power level.

Efficiencies of both HITU transducers at resonance frequency are between 70-80 % that is consistent with manufacturer specifications declared in data sheets of transducers. The three calculations agree within approximately ±5% at frequencies close to resonance where the phase angle of the transducer impedance is within about ±45°. In this range, $P_1$, determined using the voltage and current probes, lies between $P_2$ and $P_3$.

5. Discussion and conclusions

Parts of this work have highlighted the significance of harmonic distortion in the drive signal. Harmonics produce power half cycles of different amplitude and shape, and that a reactive load impedance results in each power half cycle itself being asymmetric. In practice, the output of many HITU amplifiers will be distorted: whilst this usually only has a small effect on the acoustic output power, it can introduce large errors when measuring electrical power if the amplitude of the voltage or current is used to calculate power. It also becomes difficult to determine the phase between voltage and current in the time domain for a reactive load as the two waveforms have different shapes. Even when simply determining an applied voltage (for instance to calculate radiation conductance), voltage amplitude or peak-to-peak value should not be used when there is the possibility of distortion. The $\text{rms}$ voltage or, perhaps better, the magnitude of the spectral component at the fundamental frequency should be determined.

Attempts to create a low impedance current shunt to be placed between the amplifier and transducer were not successful. Instead, the method which seems likely to offer lower absolute uncertainty is to measure simultaneously voltage, current and relative phase using commercial voltage and current probe. Input electrical powers were calculated in three different measurement methods and compared their measurement results with ultrasonic power for two HITU transducers. Measurements were realised at around 1 MHz for low power levels. An analysis of the uncertainty in using simultaneous voltage and current probes to determine power has not yet been carried out. The method also needs to be tested at higher frequencies and power levels.

6. References

[1] IEC61161:2007. Ultrasonics – Power Measurement – Radiation Force Balances and Performance Requirements. International Electrotechnical Commission, Geneva, 2007

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