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PWM BASED LOCK-IN BIOIMPEDANCE MEASUREMENT UNIT FOR IMPLANTABLE MEDICAL DEVICES

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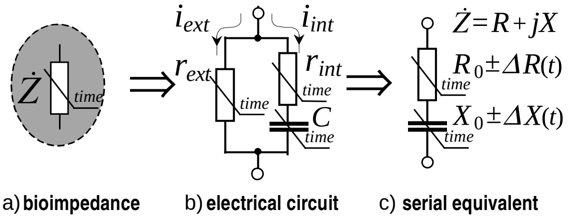
Abstract – A method for design of the switching mode lock-in bioimpedance measurement unit is proposed. The unit is foreseen to use in implantable medical devices for making medical experiments *in vivo*. The solution is aimed to lessen the errors caused due to sensitivity of the switching mode lock-in signal converters to the odd higher harmonics of an input signal. The applied method is similar to pulse width modulation (PWM), and it is oriented to achieve minimal complexity and low energy consumption.

Keywords: electrical bio-impedance, lock-in measurement, implantable medical device.

1. INTRODUCTION

Measurement of electrical bio-impedance (EBI) by implantable or portable biomedical devices gives valuable information about biological processes [1].

As the bio-impedance has a complicated equivalent circuit (Fig.1), measurement of the components R and X of the complex impedance, which are mutually in quadrature, must be performed with required accuracy. It means that accuracy of separation of complex components is not less important than the common calibration accuracy (Fig.2).



a) **bioimpedance** b) **electrical circuit** c) **serial equivalent**

Fig. 1. Electrical equivalents of bioimpedance

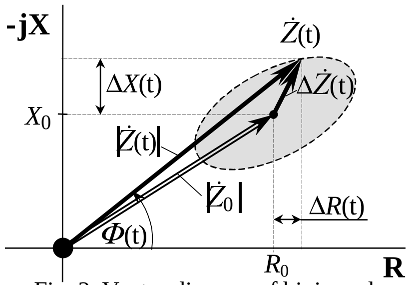


Fig. 2. Vector diagram of bioimpedance

Not only the components R and X itself are of interest, but also their relatively small time variations $\Delta R(t)$ and $\Delta X(t)$, which are caused by biological processes in biological objects discussible as biomodulation (Fig.2). In fact, the situation occurs to be quite complicated for the implantable devices, which must satisfy numerous restrictions to their size, power consumption, etc.

One can use different principles of impedance measurement, but the lock-in signal conversion or synchronous detection (SD) method [2, 3] is most often chosen because of its inherent noise suppression ability and suitability for phase sensitive measurements. Separate synchronous detection of the inphase and quadrature components allows obtaining the real and imaginary parts R and jX of the complex impedance $\dot{Z}$ separately (Fig.3).

Unfortunately, the simple switching mode synchronous or lock-in detection, known also as synchronous rectification, is strongly sensitive to the odd higher harmonics of the fundamental frequency of excitation signal depending on the content of harmonics in the rectangular reference waveform [2, 4]. So the pure sine wave excitation signal should be used in synchronous rectifiers, and non-linearity of the object under investigation should not cause significant higher harmonics in the response signal V_Z.

As it is cumbersome to obtain the stable sine wave excitation in practical circuits, the rectangular waveform substitutes are commonly used in implantable units [1].

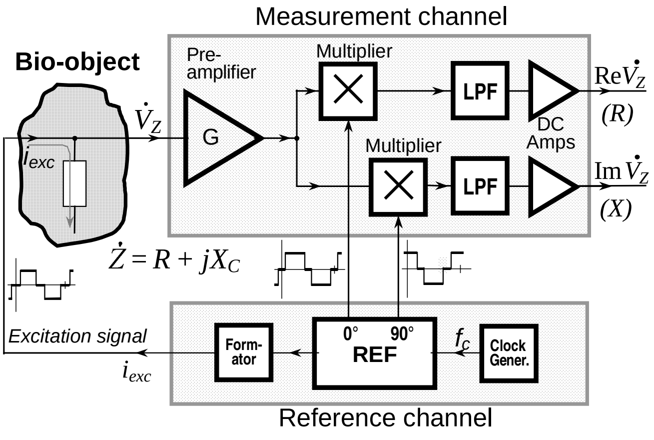


Fig. 3. Block diagram of lock-in bioimpedance analyser using modified rectangular waveforms

2. PROPOSED SOLUTION

2.1. General considerations

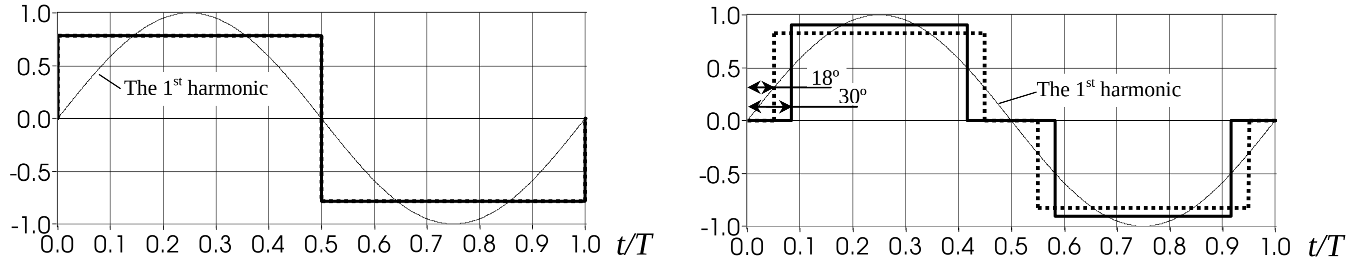
The aim is to find a way how to modify the traditional lock-in system, operating with rectangular reference signals [3], without introducing significant complexity. One should find possibilities to reduce the higher odd harmonics content of the rectangular wave excitation signal, and to decrease the sensitivity of switching-type synchronous detectors to the lower order higher harmonics of the excitation signal [4-7].

The simplest suitable approximation of sine wave is obtainable by shortening of the rectangular signal pulses and introducing of zero-level intervals (Fig.4), i.e. one can use three signal levels (+A, –A and 0) instead of two levels (+A and –A) as usual. This approach can be considered as an application of a specific pulse-width modulation (PWM) to the pulse signal.

2.2. Suppression of harmonic effects

Study of the spectral properties of the pulse width modulated (PWM) waveforms showed that, from all the easy-to-generate waveform pairs with maximally different harmonic content, the best one consists of waveforms having 18° and 30° pulse shortenings (Fig.4).

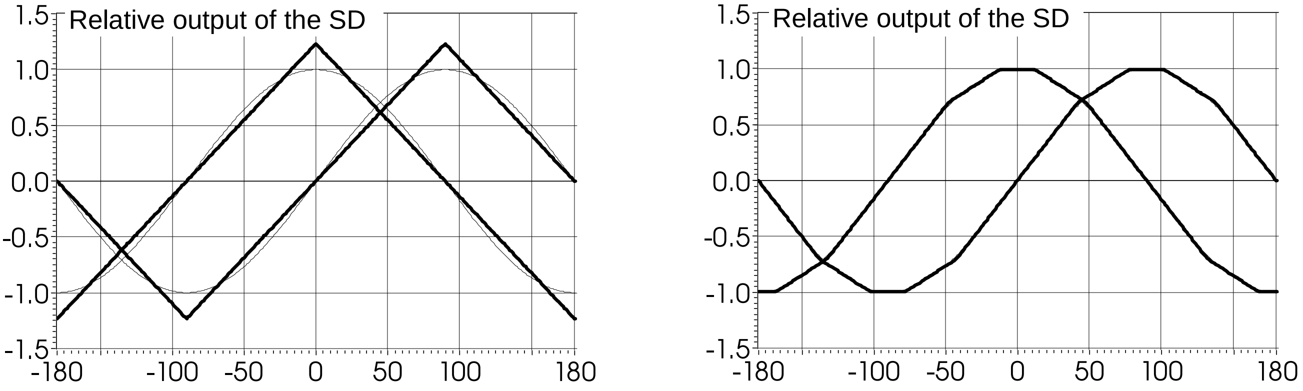
There is not the 3rd, 5th, and 9th harmonics in both of these waveforms, but the 7th harmonic exists in both of them though it is somewhat more suppressed in one signal (Fig.6).



a) rectangular waveforms with full duty cycle

b) rectangular waveforms having duty cycle shortened by 18° and 30° (the PWM)

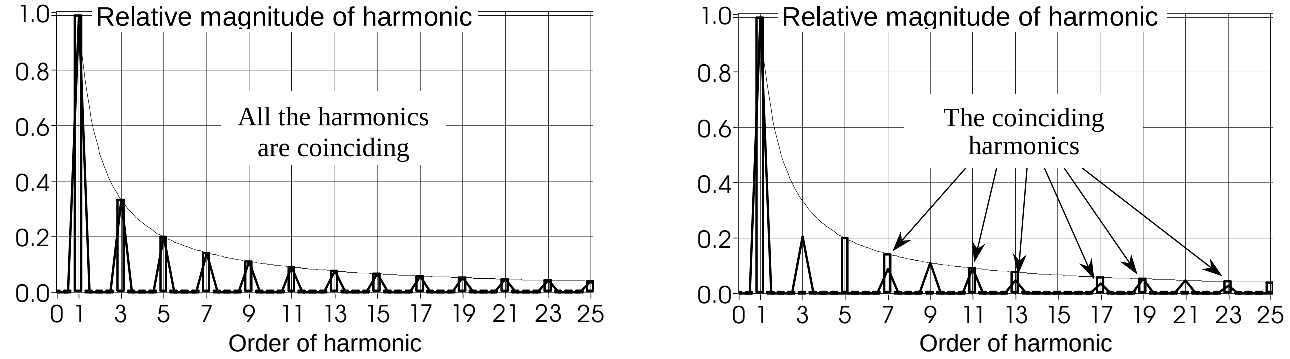
Fig. 4. The rectangular waveform reference and excitation signals (the case of zero phase-shift)



a) the case of rectangular waveforms with full duty cycle

b) the case of rectangular waveforms having duty cycle shortened by 18° and 30° (the PWM)

Fig.5. Output for inphase and quadrature components in the case of rectangular waveform reference and excitation signals with full duty cycle (a) and with shortened duty cycle (b), shown in Fig.4, $\Phi = -180^\circ$ to $+180^\circ$



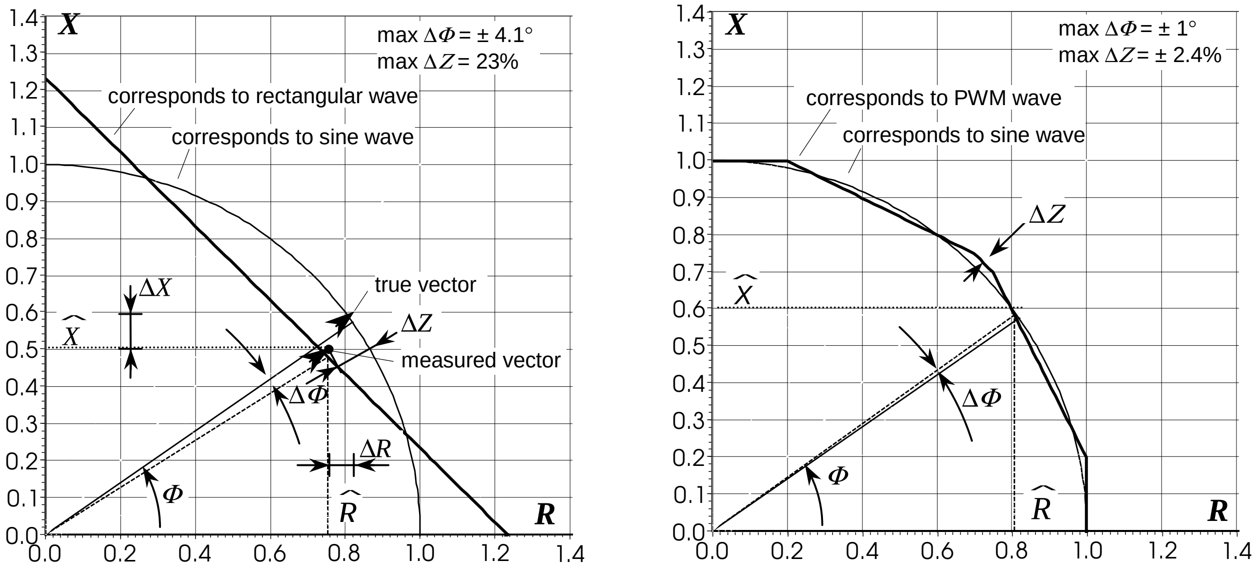
a) the case of rectangular waveforms with full duty cycle

b) the case of rectangular waveforms having duty cycle shortened by 18° and 30° (the PWM)

Fig.6. Spectra of the rectangular waveform reference and excitation signals in the case of full duty cycle (a) and shortened duty cycle (b)

Using of the proposed shortened rectangular waveforms gives significantly different phase sensitivity characteristics of the SD gain compared to those of the full duty cycle waveforms (Fig.5). The situation is very similar to the pure sine wave case, where the SD gain has a cosine form for the inphase SD output and the sine form for the quadrature SD output over the full phase cycle (from –180º to +180º in Fig.5).

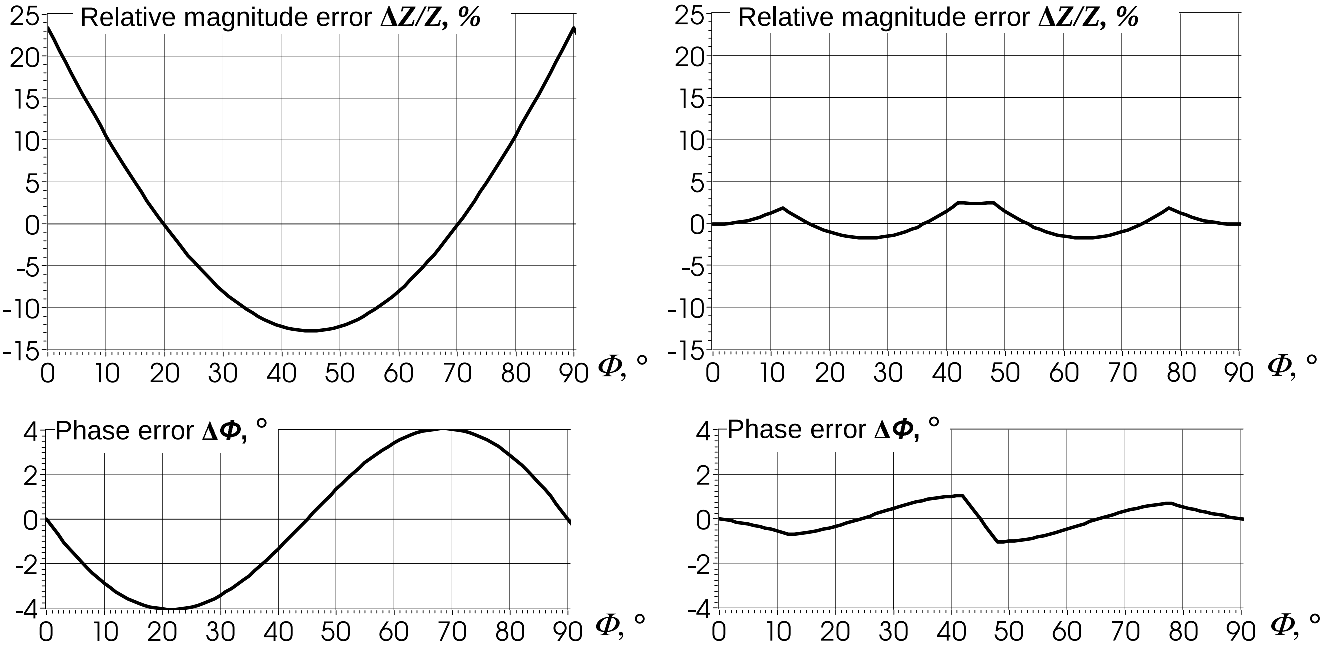
Comparison of phasor errors in the described two cases of using rectangular waveforms shows that the shortened waveforms have clear advantage over the full duty cycle waveform (Fig.7 and Fig.8). The ideal sine wave input gives us the perfect arc of circle as the trajectory of phasor tip over the first phase quadrant (fine line in Fig.7 and Fig.8). This trajectory can be considered as a basis for comparison.



a) the case of rectangular waveforms with full duty cycle

b) the case of rectangular waveforms having duty cycle shortened by 18º and 30º (the PWM)

Fig. 7. Phasor errors (magnitude error ΔZ and phase error ΔΦ) due to application of rectangular waveforms in the case of full duty cycle (a) and in the case of using the shortened duty cycle (b)
The errorless case of using pure sine wave is indicated in form of the arc of a circle (fine line), only one quadrant is shown.



a) the case of rectangular waveforms with full duty cycle

b) the case of rectangular waveforms having duty cycle shortened by 18º and 30º (the PWM)

Fig.8. Magnitude error (ΔZ) and phase error (ΔΦ) in the case of rectangular waveform signals instead of the sine-wave signals

The inphase and quadrature outputs of the full duty cycle SD draw the straight sloped line, which is a side of rectangle in the case of full duty cycle excitation waveform (Fig.7). The straight line is quite different from the arc of circle obtained in the ideal sine wave case, and corresponding magnitude and phase errors (Fig.8a) are evidently too big.

In the case of shortened pulse (PWM) waveforms, the SD outputs fit to the ideal sine wave case quite well, though the waveforms in fact remained rectangular. The corresponding magnitude and phase errors in Fig.8b are about ten and four times smaller than in the full duty cycle case.

2.3. Synchronous Detector

Fig.9 demonstrates a circuit solution where only the multiplexer in the ordinary switching type SD [2,3] is modified so that the third grounded position is introduced to achieve the operating mode with shortened pulses [8].

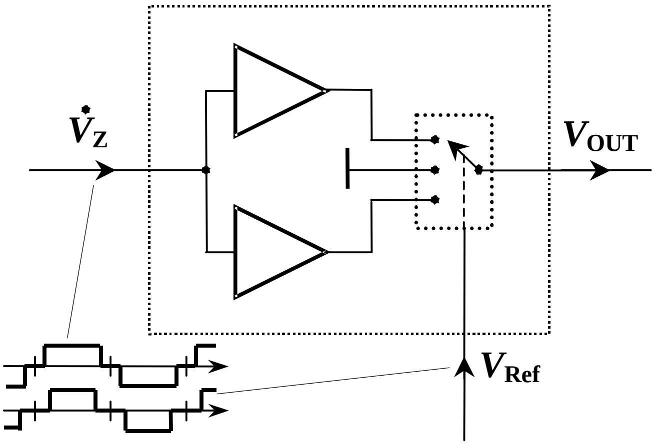


Fig. 9. Cicruit diagram of the shortened-pulse (PWM) Synchronous Detector

Much more changes must to be done in the generator of excitation and reference signals. Fortunately, this is a trigger circuit, which is relatively easy to modify adding needed number of elements. The $18^{\circ}/30^{\circ}$ shortening requires the clock frequency, which is 60 times higher than the signals have ($f_c = 60 \cdot f$). Of course, the current consumption of trigger circuitry grows up with the number of elements, and especially with the higher clock frequency.

2.4. The frequency response measurement

The frequency response of bioimpedance $\dot{Z}$ has a capacitive character, which is falling towards higher frequencies, though its slope is very slight due to dielectric dispersion in the biological objects [3]. Anyway, the bio-impedance can not rise up higher harmonics. As a result, any higher harmonic in the response voltage V_Z can not become higher than it is in the excitation current. Therefore, we can consider the harmonic content of the excitation signal as the worst case for the response signal.

To perform the frequency response analysis of the bio-impedance, one has to apply the excitation at least at two frequencies distant enough from each other. As the experments are carried out commonly in nonstationary *in vivo* conditions, the both excitations must be applied to the bio-object simultaneously. Otherwise the erratic deviations can appear in the results because of perpetual changes in the state of living organism or tissue (breathing lungs, beating heart, rythmic blood flow, etc.).

Simultaneous two-frequency measurements can be also performed using the tri-state circuits for generation and processing of excitation and reference signals. The simplest way to provide independence of the responses (that is, to prevent coincidences in their spectra) is to ensure that the excitation frequencies relate to each other as even numbers, preferably as the binary-rate ones.

3. CONCLUSIONS

The proposed solution of lock-in signal conversion on the basis of PWM is simple enough to be used in the implantable biomedical devices. It gives adequate phasor measurement results for bioimpedance measurement and analysis.

The proposed PWM method for performing the two-frequency excitation and detection needs further development to obtain sufficiently simple and elegant solutions.

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