# Electrical impedance tomography – Lock in Amplifier

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***Abstract*— The practical realization of this system demanded high speed multichannel parallel algorithms which could only be implemented in the FPGA technology. The device is intended for use in multiple medical researches such as determining the influence of the medical probes on the living tissue, measuring deviations in the impedance between healthy and diseased tissue, registering the presence of viruses in the blood samples and analysis of the brain bio-electrical signals. The two essential reasons for using a Lock-In amplifier in a scientific experiment are its ability to "reduce noise", i.e. to improve the Signal-to-Noise ratio of the signal to be measured, and to do phase sensitive detection, the latter being mainly deployed in technical applications, as e.g. in phase locked loops and control circuits.**
***Keywords:*** biomedicine, lock in amplifiers, brain signals, FPGA platform, extreme noise environment

## I. INTRODUCTION

The bioelectrical signals over the years became the primary source of the information used for disease diagnostic. The bioelectrical signals are used in the human body for communication and process control within the human organism. Therefore by monitoring those signals it was possible to notice deviations in case of disease, injury or foreign tissue like cancer cells. Every living cell in the human body generates some form of bioelectricity. This is the biggest problem in the biomedicine because this means extremely noisy environments. In practice it is very difficult to isolate the bioelectrical signals of interest and disregard all the other signals. Furthermore, most of the time the observed signal is much smaller than the surrounding noise. For instance, if one applies the electrodes to a person's forehead in order to detect brain waves, every time when the person blinks, muscles around their eyes will emit the bioelectrical signals that are thousands of times stronger than the measured brain wave. The bioelectrical signals are alternating current by nature and therefore require special equipment for detection. Because of all this the biomedicine stands for an extremely challenging scientific discipline and practical solutions are always obtained by the utilization of the multidisciplinary approach. That means that medical, electronic and IT expertise are required [1].

In order for the biomedical research to be performed on new ideas and methods it was necessary to design a device which could answer to the technical requirements needed for such a research. Signals are electrical by nature and are transferred through living tissue to the measuring probes. The living tissue in electrical manner has impedance and that impedance represents the state of the organ (healthy or diseased). This meant that the device had to be able to generate AC signals of variable amplitude and frequency which would be introduced into the tissue and also to be able to measure impedance, amplitude and frequency of the received signals after they had traveled through the organ. Since the noise was extremely high for accurate detection of the injected signals lock-in amplifier technique was used [2].

This paper describes the developed instrument which could be used even outside the biomedical area, for instance, for a range of measurements in geodesy on soil samples.

## II. DEVICE DESCRIPTION

The system has three different parts:

- Analog board
- Digital board
- PC software client

The analog board performs D/A, A/D signal conversion and also provides a physical link with the electrical probes. The analog board has to provide minimal noise introduction into analog signals. The digital board performs signal processing including spectrum and impedance calculation. The FPGA chips on the digital board were used for all time critical operations, while the ARM processor was used slower algorithms and communication with PC client. Utilization of FPGA technology allowed the simultaneous measurement of multiple channels whereas with the classical approach one board could handle one data signal at a time. The digital board can simultaneously receive 8 data signals and by multiplexing it can handle up to 64 channels. The digital board also has an SD card installed so it is possible to use the entire device as standalone without the need for interfacing with a personal computer. The PC software client receives data and displays the results graphically.

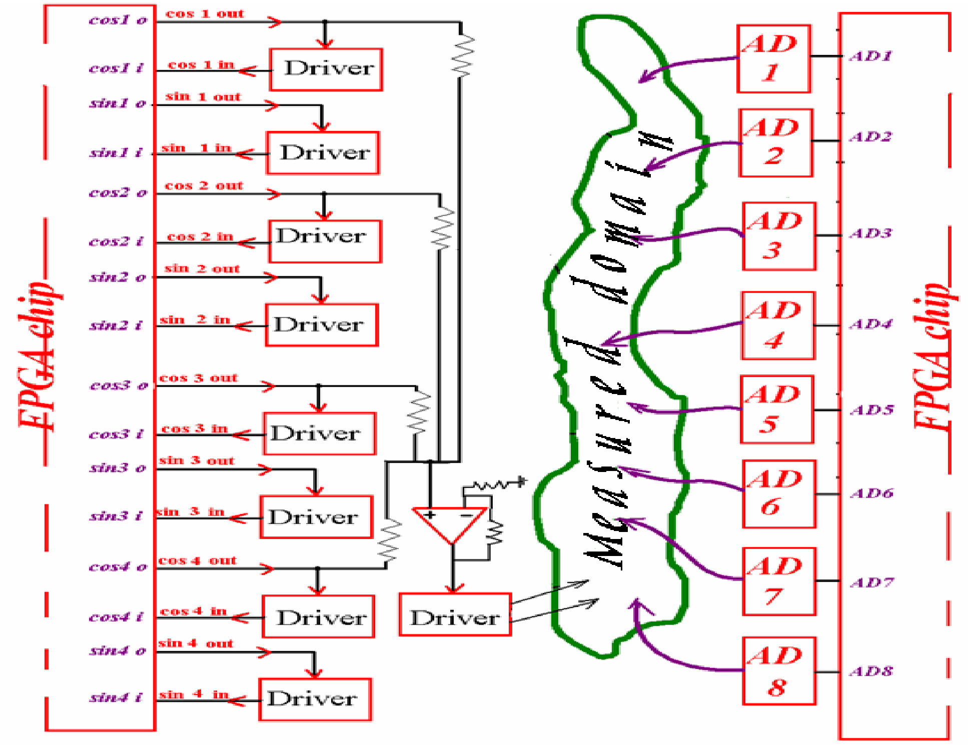


**Figure 1.** Principle of the 8 channel measurements

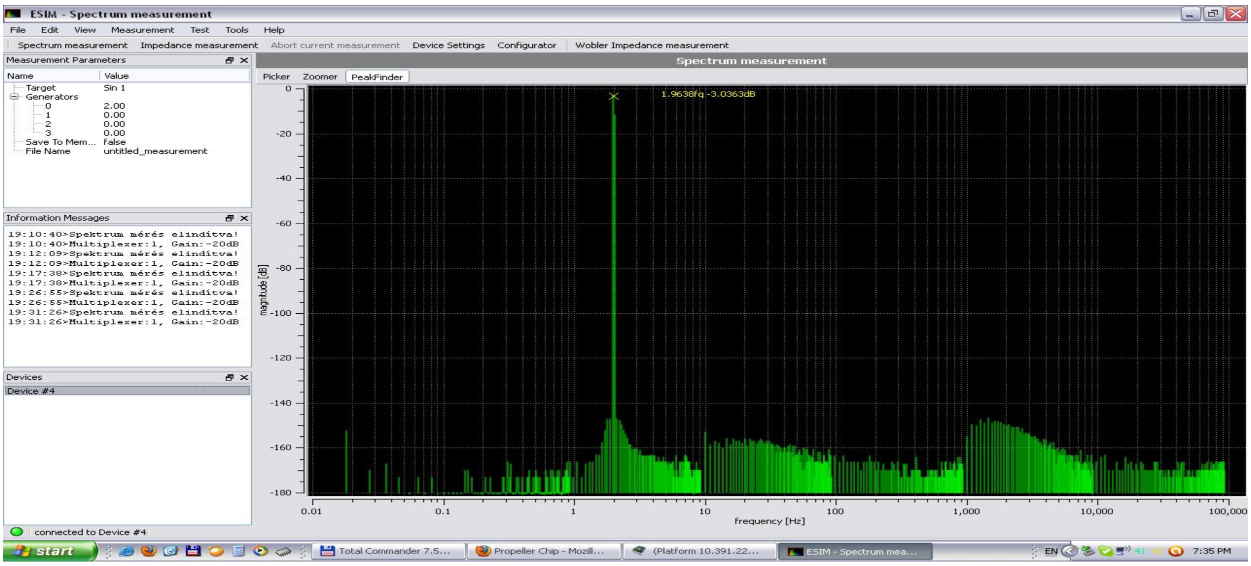


**Figure 2.** Spectrum measurement of the 2Hz signal that was generated by the digital board and then received by the digital board without the analog board.

Figure 1 presents the logical schematic of the system. The most sensitive part of the system is the analog board because the measured signals have very low amplitude and therefore are very sensitive to noise. Figure 2 shows the spectrum measurement of the 2Hz signal that was generated by the digital board and then received by the digital board without the analog board. This example clearly indicates that the analog board introduces about 20-30dB noise into the frequency spectrum. This means that any signal manipulation must be done on the digital board and the analog board must provide clean routing for analog signals to avoid noise introduction.

The characteristics of the device:

- the basic unit has 8 channels which can be multiplexed on the analog board to 64 channels,
- the measurement was based on the "lock-in" method,
- multiple basic 8/64 unit can be combined together in parallel for measurements on N x 8/64 systems. The current system has N=32, but it is possible to achieve several thousand channels,
- measure range: 1 Ohm – 100 MOhm and 0-90 degrees,
- output range for impedance is maximum 100Hz (in frequency range of 10-90kHz),
- the maximal sample frequency is 187.5kHz and the data band of the AD converter is 24bit/sample,
- the accuracy of the system is above: 0.01% and +/- 0.01 degree,
- the range of measuring frequency: 0.01Hz - 90kHz.

## III. Implementation

The goal was to measure and display the spectrum of 7 decade digital signal under the following criteria:

- the targeted range between 0.01Hz and 90kHz,
- measuring p=100 frequency points per decade and distinction m=50 frequency values per decade,
- measuring magnitude between 0dB and -160dB,
- representation of the digital signal was in Q23 (int24) format.

The sample frequency was Fs=187500Hz so in order to measure Fp=0.01 Hz signal it was necessary to develop an FFT algorithm of minimal order of n=Fs/Fp=18 750 000. This would require at least 300MB of memory and a vast amount of computing power which was practically impossible to achieve with ARM processors [3].

The solution to this problem was found by dividing the sample rate frequency into three separate measurement bands, each performed in sequential time sequence. All three bands cover 2 decades of frequency range, proximally 100 points/decade and also the third (lowest) decade with 10 points.

In order to achieve 100 frequency points in the lowest decade, FFT algorithm requires at least 1000 points, so resulting order of FFT would be 2000. Therefore FFT of order n=2048 was selected. For the upper decade it is required to have 1024-102=922 points, so decimation of factor 9 was introduced to reduce the number of points. In the first step device collects 2048 samples and then the FFT algorithm calculates the frequency points for the upper two frequency decades. After that signal is sampled through the decimation procedure of factor 100 (Fs=1875Hz) and after the FFT algorithm two new decades are obtained. In the third step the sample rate is reduced by the factor 100*100 by decimation process and that allows the calculation of frequency points in the lowest decade.

## IV. WINDOW DESIGN

In order to display the values for the spectrum in the range to -160 dB it was necessary to design a window of an order n=2048, which is capable to suppress FFT leakage occurrence on -160dB. The window with those parameters could separate two nearby frequency values, but still be able to achieve noise suppression below -160 dB as presented in Figure 3 which displays simulation results.

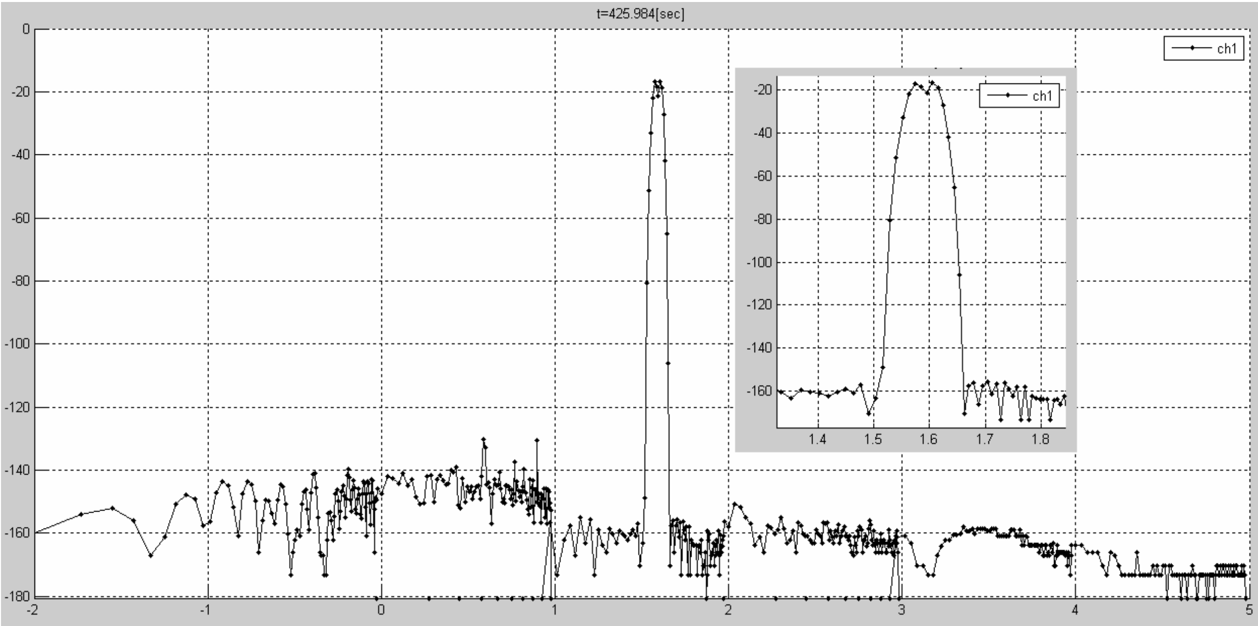


**Figure 3.** Two adjacent frequencies (40Hz +42 Hz) spectrum display

Two groups of digital filters were designed:

- decimation filter (for use in spectrum measuring), were designed in advance,
- band pass filter, have to be calculated dynamically from PC application by users runtime specifications.

The filters were implemented in processors with fixed decimal point TAS3108 [3] with 28 bit precision (5Q23 format) and in SOS (Second Order Section) structure. In order to achieve large noise suppression IIR filters of order 20 (10 biquads) were used.

The process of quantization was comprised by applied rounding: 6 rounding methods are available for selection, which can greatly improve the accuracy of the filter in the extreme condition as presented in Figure 4.

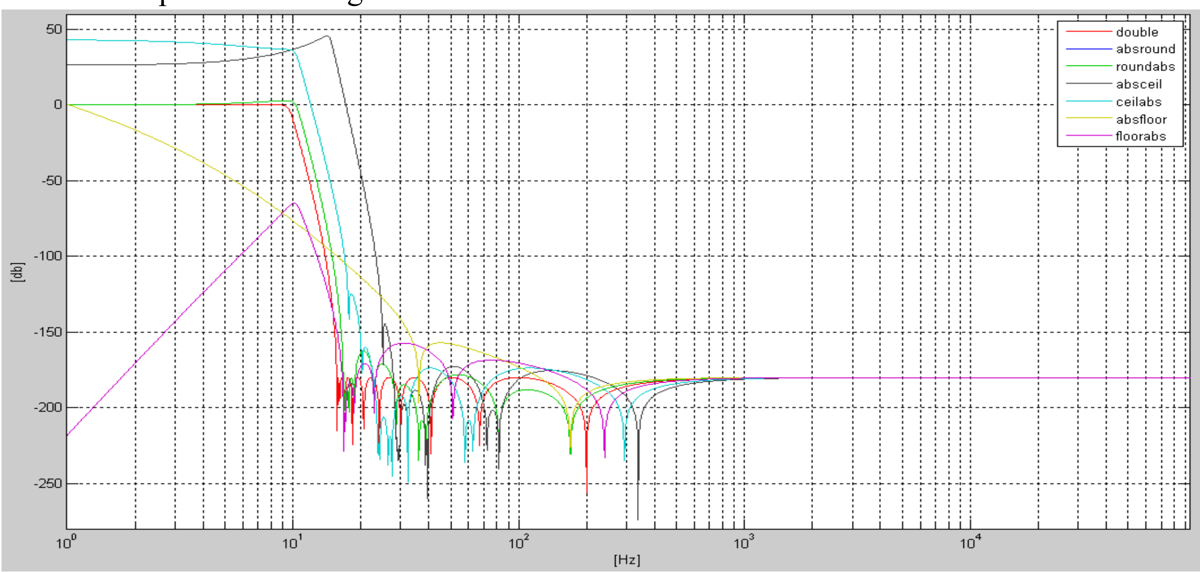


**Figure 4.** The process of quantization was comprised by applied rounding

As presented in Figure 5. the GUI (Graphical User Interface) contains logarithmical graph and parameters required for design which will be transmitted over to the IIR filter design unit written in C#. By specification of the contractor it was required for the GUI to be able to modify the width of frequency characteristic of band pass filter which was specially marked on the previous picture. Parameters Cutoff frequency (FCutOff) and band pass width (WBP) were used for this purpose in the following manner:

$$F_{center} = F_{CutOff} \quad (1)$$

$$F_{high} = F_{center} \cdot \frac{1}{1 - W_{BP}} \quad (2)$$

$$F_{low} = F_{center} \cdot (1 - W_{BP}) \quad (3)$$

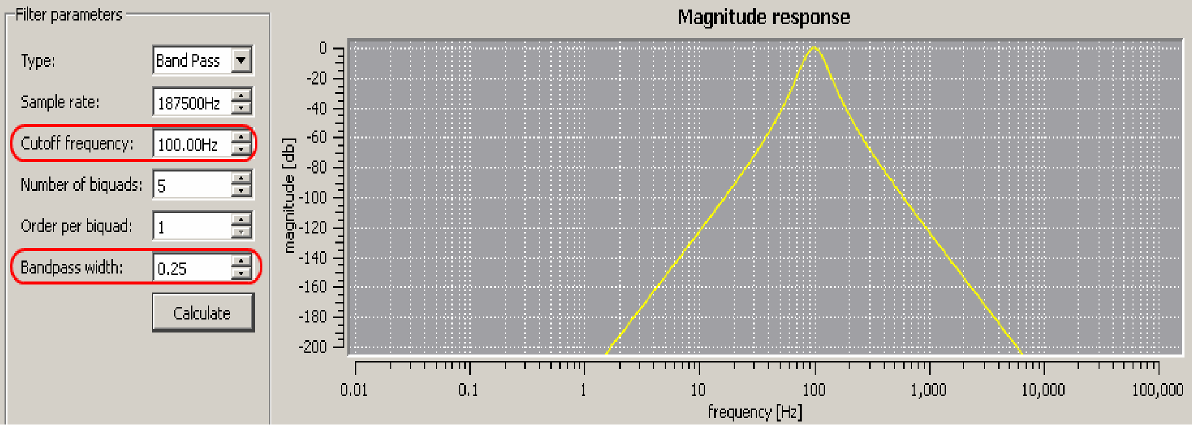


**Figure 5.** Design process of IIR bandpass filter

## V. PC CLIENT

The PC application presented in this section, called ESIM, served as a development tool. The electronics engineers have used the application to test the behavior of the measurement system. It served as a general purpose tool intended strictly for the development team. ESIM represents a good starting point for developing custom management applications for the measurement system, for various specialized fields of use.

ESIM was created to run on the Windows platform. It was written in the C++ programming language; it employs almost exclusively cross platform software libraries and frameworks. These properties of the application will make the porting of the application to other software platforms easier and quicker in case the need arises. The architecture of the management application was designed to allow for the development team to change the method of communication between the application and the measurement system without affecting the rest of the software solution. ESIM went through several of these changes during the development process. At the end, communication through the USB interface proved to be the most adequate solution for the needs of the measurement system. In fact, the software module of the application which is responsible for handling the communication through the USB interface is its only platform-dependent part.

The main window of the application consist of a menu bar, tool bar, various docking windows, status bar and from a central area where the measurement results are displayed as presented in Figure 6. The menu bar contains the shortcuts for every operation supported by the application, the most frequently used ones are also displayed in the tool bar. One of the dock-able windows displays a list of the measurement devices connected the PC on which the ESIM application is running. This window allows the operator to select the targeted device from the list, on which he wants the application to act. The connection to the currently active device is indicated in the status bar. The remaining two dock-able windows display additional information for the operator during ongoing measurements, like the parameters of the currently running measurement operation, and textual messages sent by the measurement device. Every measurement device has a unique identifier and role in the system, they can operate in master or slave mode. By convention every device connected to the PC has to be configured with a distinct identifier and only one of them can be configured to operate in the master mode. If the application detects that any of these rules are violated, it will disable all the measurement starting functionality of the software, and it will allow the operator to alter the configuration of the connected devices in the device settings window. Besides the device's identifier and role in the system, this window allows the operator to alter every configurable property of the target devices' analog and digital board.

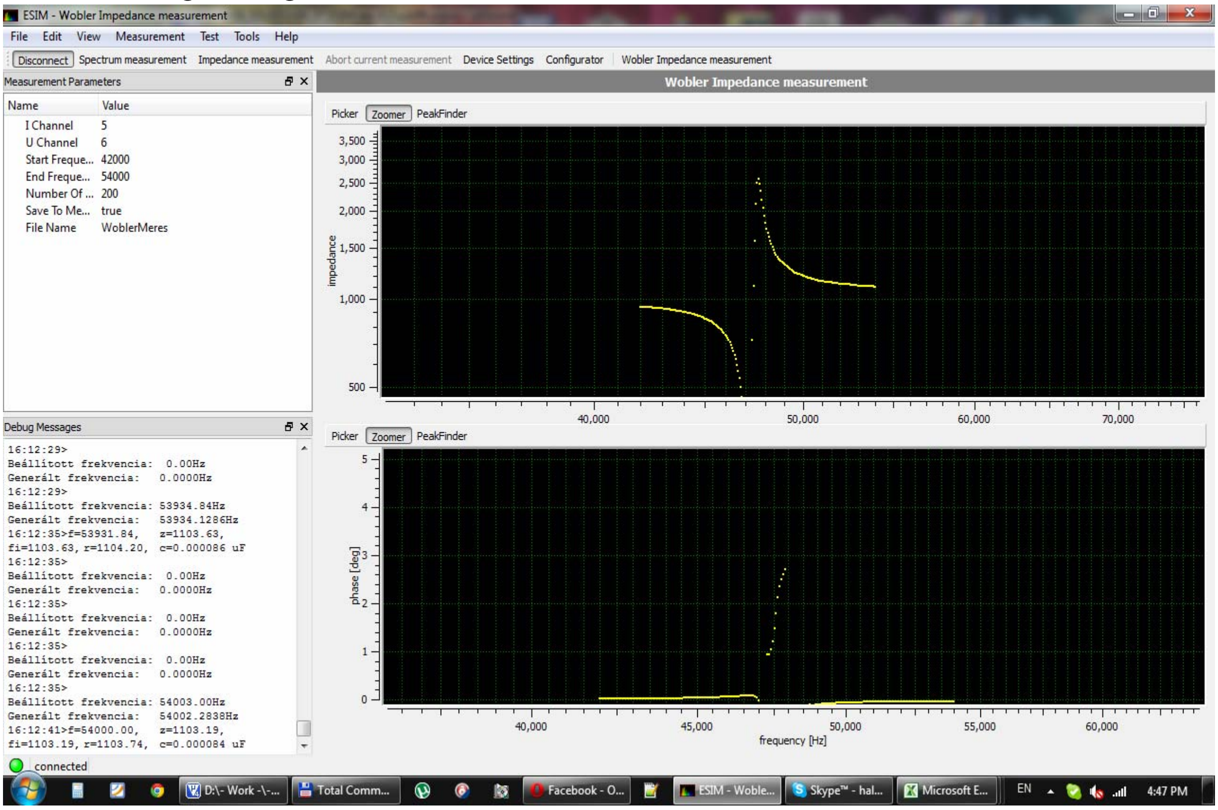


**Figure 6.** Wobbler Impedance spectrum analysis

From the user interface of the management application all the measurements can be started which are supported by the measurement system, either instantly on the selected target device, or at a specified time in the future by creating a so-called measurement configuration file. In a separate window of the application, called the measurement configurator, the operator can construct a series of precisely timed measurement operations. This series can be saved in a measurement configuration file either in a non-volatile memory of the PC or directly to the measurement device.

Before a new measurement can be launched the operator must configure the measurement procedure. For every kind of supported measurement type, a configuration window will appear. When launching a spectrum measurement several different parameters must be configured first. The target parameter represents the signal that will be measured by the device. The operator can chose from twelve options, from which eight are the device's input channels, and the rest of the options are sine and cosine waves generated on the measurement device.

There are four optional signal generators, which can be configured for the measurement; at least one of these must be enabled to be able to start the measurement. Their configurable frequencies can be set in 0.02Hz steps, and they range from 0.02Hz to 90000Hz. Optionally the results of the measurement can be saved in a non-volatile memory of the measurement device, with a filename defined by the operator. The entire results for the spectrum measurement are delivered in three steps to the application, which will be displayed in the central area of the application after the measurement has finished.

An impedance measurement can be started in two modes. In the mode called 4U-4I, four input channels will be dedicated to voltage measurement and the remaining four to current measurement. The results are displayed as a vector in four Cartesian coordinate systems. In the mode called 7U-7I, seven channels will be dedicated to measuring voltage, and the remaining one for measuring current. The results in this mode are displayed in eight coordinate systems.

Optionally four signal generators can be configured for an impedance measurement, and a filename for saving the results, the same way as for the spectrum measurement. The duration and the delay between separate impedance measurements can also be defined. A window is provided for designing the digital filter which will be optionally used for filtering the input signals before it reaches the operation that calculates the results. The A, B, C and D parameters, which are required for calculating the values of impedance intensity, angle of phase, resistance and capacitance are displayed below the coordinate systems in the measurement results area of the application.

During impedance wobbler measurement, in fact the 7U-1I impedance measurement configuration is used, the only difference is that instead of 7 input channels only one of them can be used for measuring voltage. In the impedance wobbler measurement configuration window, the IDs of the input channels should be entered which will measure the voltage and current, as well as the range and number of frequencies that will be used during the measurement. The results of the measurement are displayed in two Cartesian coordinate systems, aligned vertically. On their horizontal axis the frequency is displayed on a logarithmic scale. The vertical axis of the higher coordinate system represents the imaginary component of the results and the vertical axis of the lower coordinate system represents the real component.

## ACKNOWLEDGMENT

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## CONCLUSION

This paper described the developed instrument for accurate measurement of bioelectrical signals. The key benefit of the proposed solution is the system’s extreme noise suppression ability which is vital in the detection of low bioelectrical signals. This allows the implementation in medical equipment for diagnostics. This research also showed that, in cases when fast parallel data processing is required, the FPGA technology presents the only viable solution.

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