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Interfacing the AD5933 for bio-impedance measurements with front ends providing galvanostatic or potentiostatic excitation

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Abstract The AD5933 [1], a specialized single chip impedance analyzer, made by Analog Devices, is basically not intended for use with four electrode interface. Due to electrochemical phenomena at the electrodes connecting the material under test (MUT), especially in the low frequency region below 100 kHz, a two electrode interface generates considerable errors during the measurement. Thus, for most application in bio-impedance measurement only a four electrode interface can guarantee reliable results. Here we show how a four electrode interface with galvanostatic excitation but also for potentiostatic excitation can be realized by just a few external components.

1. Introduction

Bio-impedance measurement is a simple and innocuous way for electrical characterization of cells and tissue. If the important information is expected to be the conductivity of a suspension medium or the integrity of the cell membranes, low frequency measurements between some Hz up to MHz are advisable. The frequency range of the AD 5933 without external components - from 5 kHz up to 100 kHz - is therefore well suited for many applications in bio-impedance measurements. Using an external divider, one can synthesize lower frequencies. This however, is behind the scope of this paper.

A great advantage of the AD 5933 is the simple programming via I²C-bus and a fully functioning device with just a few components. However for bio-impedance measurements some shortcomings are essential and need to be addressed:

- The dynamic range for the impedance of the material under test (MUT) is only two orders of magnitude. Although numerous bio-impedance applications for MUT with only small variation exist, the impedance of biological MUT ranges often over several orders of magnitude.
- In low frequency applications below 100 kHz, the contact between the MUT and the electronics is usually mediated by electrodes. Therefore, the electrode polarization will add considerable serial impedance (polarization impedance) to the MUT which can be on the order of the MUT-impedance or even bigger, yielding quite wrong results. A widely used approach to compensate the polarization impedance is the four electrode interface where a current is applied between two electrodes and the voltage monitored across a second pair of electrodes. The AD5933 is not intended for use with a four electrode interface.
- Due to the trans-impedance at the input of the AD5933, a measurement with respect to ground is only possible with external components.
- Most bio-impedance measurements require offset free excitation which is only possible with external signal conditioning.

Several applications of the AD5933 for measuring bio-impedances using a four electrode interface are already shown [2-3]. The principle of the analog interface is a symmetric current source, controlled by the output of the AD5933 and a voltage-current converter feeding the voltage dropping at the voltage monitor electrodes into the input. In [2] a comprehensive analysis of the precision achieved with this circuit connected to the analog interface in comparison to a commercial impedance meter showed useful performance of this circuit.

Our activities concentrate on the use of miniaturized electrodes with either bare metal surface but also passivated electrodes for online measurements on fluids, cell suspensions and other organic material. Therefore, we adapted the AD 5933 with a four electrode interface for galvanostatic (similar to [2] and [3]) but also potentiostatic excitation of the material under test.

2. Principle of the AD5933

The AD5933 is made by Analog Devices (Norwood, MA, USA) as single chip impedance converter. It contains everything from frequency synthesis, signal conditioning and –processing up to the I²C-interface. Both, the excitation signal (intern, no user access) and the answer signal are sampled (1024 sample points) and Fourier

transformed in order to get the real and imaginary part of the ratio between signals. In case of voltage excitation and current monitored, it is directly the electrical impedance. Due to the low frequency, the group delay within external components is not important. Thus, interfacing with additional operational amplifiers will not seriously compromise the performance of the device. The internal signal conditioning with programmable gain amplifier (1x or 5x) allows a limited dynamic range but requires for most applications additional conditioning using the analog front end.

3. Galvanostatic excitation

For most applications of bio-impedance measurement using a four electrode interface, galvanostatic excitation is advantageous [4]. The basic principle of the symmetric current source, controlled by the output of the AD5933 is a Howland-circuit using an operational amplifier with symmetric output (AD8132) together with a reference resistor (Fig.1). The signal after the R_{REF} is feed back to the non-inverting input via buffer amplifier. The resistors R5/R6 are used for attenuation (1:10) of the 1.98 V – output of the AD5933. A second R_{REF} with the same value is used at the negative side in order to ensure symmetry of the current flow with respect to ground. The offset of the AD5933 was removed using a feedback loop as shown in detail in [4]. The voltage dropping across the inner electrodes (voltage monitor electrodes) is amplified using a difference amplifier (AD8130) which is optimized for a gain of 1. If a higher gain is necessary, this circuit should be exchanged for the AD 8129. Although not shown here, we always use input buffers for the AD8130 since the input impedance is rather low and would cause a mismatch with the high impedance miniaturized electrodes reaching sometime up to many k Ω . Since the AD5933 – input is not designed for offset free operation, we added the offset using the reference input of the AD 8130/8129.

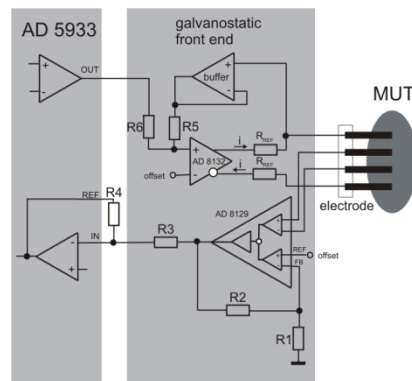


Fig.1 principle of AD5933 coupled to a four electrode interface with galvanostatic excitation

The reference resistor is between 100 Ω and 10 M Ω which allows setting the excitation current between 200 nA and 2 mA. A lower current is possible but does not make sense for the electrode devices we used because of considerable parasitic capacitances resulting in a very low signal between the inner electrodes.

It should be noted, that the output is the current divided by the voltage and is therefore the reciprocal of the impedance.

4. Potentiostatic excitation

If a passivated electrode is used with current excitation at low frequency, the voltage across the electrode reaches high values up to the supply voltage. Although this is usually not a problem, it becomes critical if the distance of the electrodes is low.

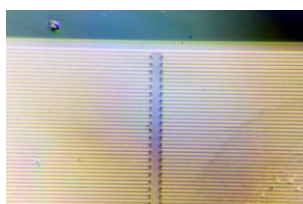


Fig.2 Miniaturized interdigitated electrode (3 μm structure repetition) with surface passivation (SiN) showing damage (bottom right) due to material migration in a high electric field (5 V applied across electrodes) .

With distances on the order of 1 μm , the field strength may reach up to 5 MV/m with a supply voltage of 5 V. This is sufficient for causing material migration and finally a failure of the electrode (Fig.2.)

In order to prevent electrode damage but also for measurements where the electric field strength plays an important role, we constructed a front end where the voltage between the voltage monitor electrodes is kept constant (Fig.3). Therefore a difference amplifier (AD8130) was used where the difference voltage between the inner electrodes was feed back to the inverting input. Moreover, for the offset compensation we used the inverting input.

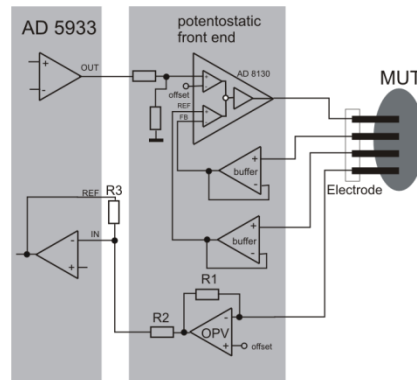


Fig.3 AD5933 coupled to a four electrode interface with potentiostatic excitation

The current through the MUT could be feed directly into the input of the AD5933. But during our tests we realized that the dynamic range of the current is not sufficient for our electrodes used. Therefore an external trans-impedance with adjustable gain (R1) was used. R2 and R3 were adjusted to meet the input requirements of the AD5933. Although it is possible to add the required offset simply by adding a voltage to the non-inverting input of the OPV used for the trans-impedance, a more sophisticated circuitry allows an offset voltage independent of the feedback resistor which is behind the scope here. Moreover, in case of small impedances, i.e. by using large electrodes and highly conductive objects like potato or meat, a very simple external circuitry consisting of only the AD8230 is possible since the input impedance of the difference input is high compared to the electrode impedance of the voltage monitor electrodes. Moreover, if an offset of $V_{DD}/2$ is used, the trans-impedance input of the AD5933 can be connected directly because the non-inverting input is internally connected to $V_{DD}/2$. This simple front end however, works only under the mentioned circumstances.

5. Sample results

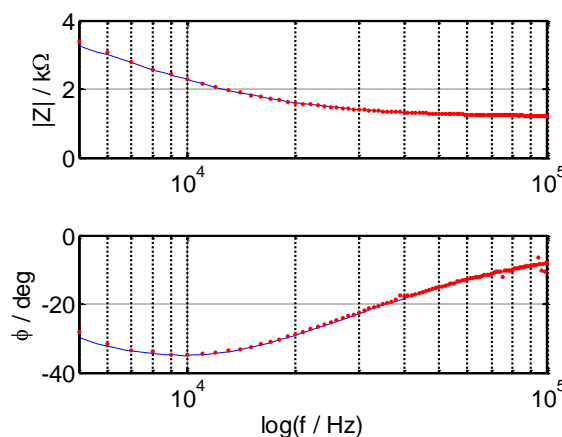


Fig.4 impedance spectrum of a parallel combination of one resistor (5 kΩ) and a serial combination of another resistor (1 kΩ) and a capacitor (1 nF) measured with an IMPSPEC-device (line) and with an AD5933 with galvanostatic four electrode front end (dots)

Simple comparison between a reference system (IMPSPEC, MEODAT Germany) and the AD5933 with both, galvanostatic and potentiostatic front end shows good coincidence. A result with a typical test dummy (5 k Ω in parallel to a series of 1 k Ω and 1 nF) is shown in Fig.4.

Using a real object, in this case a potato (Fig.5) interfaced by four electrodes (needle electrodes, 10 mm long, 2 mm diameter and 5 mm apart, shows the suitability of this circuit as well. Although not shown here, potentiostatic excitation prevented the damage of miniaturized electrodes and is as precise as the galvanostatic front end within the range of the tested impedances from 100 W up to 1 MW. A more sophisticated analysis of the precision of the analog front ends is behind the scope of this contribution and will be presented elsewhere.

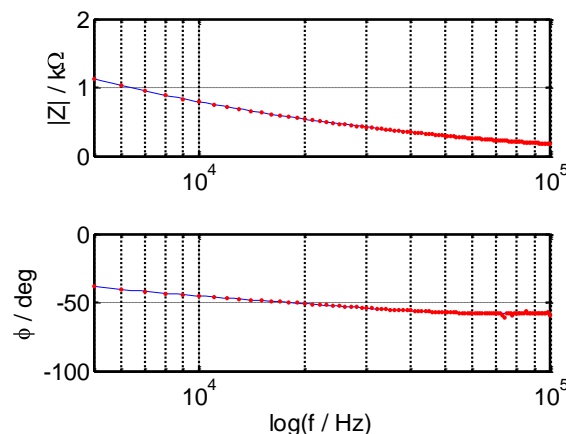


Fig.5 impedance spectrum of potato measured with an IMPSPEC-device (line) and with an AD5933 with galvanostatic four electrode front end (dots)

6. Conclusion

Although the impedance converter AD5933 is not designed for four electrode operation, a relatively simple analog front end can circumvent this shortcoming making this IC an interesting alternative for many bio-impedance applications. Potentiostatic and galvanostatic excitation can be chosen depending on the requirement of the application.

7. References

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