Bio-Impedance Circuit Design for Body Worn Systems

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Revision History

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1. INTRODUCTION

The proliferation of body worn vital sign monitoring (VSM) sensing devices is transforming the health care industry. This emerging applications allow us to monitor our vital signs and other key aspects anytime, anywhere. The most relevant information about some of these key parameters can be obtained by body-impedance measurements.

Body worn monitoring devices used in these systems have specific requirements such as minimal BOM (Bill of Material) and low power to work on battery operated systems. The measurement of bio-impedance adds challenges to these type of systems, mostly related to the use of dry electrodes and safety requirements.

This document describes challenges and solutions in the design of a low power body worn bio-impedance measurement system.

2. CHALLENGES

2.1. Electrode Half-Cell Potential

An electrode is an electrical transducer used to make contact between an electronic circuit and a nonmetallic object such as the human body. The interaction between an electrode in contact with the human skin produces a potential difference known as the half-cell potential and its value is varies depending on the electrode material. *Table 1* shows the values of this voltage for the most common materials[1].

The disadvantage of the half-cell potential is it does not provide information about the skin or body under measurement and it reduces the dynamic range of the ADC.

Metal and Reaction	Half-cell Potential (V)
$Al \rightarrow Al^{3+} + 3e^-$	-1.706
$Ni \rightarrow Ni^{2+} + 2e^-$	-0.230
$Ag + Cl^- \rightarrow AgCl + e^-$	+0.223
$Ag \rightarrow Ag^+ + e^-$	+0.799
$Au \rightarrow Au^+ + e^-$	+1.680

Table 1Half-cell Potentials

[1] Newman, M. R. "Biopotential Electrodes."
The Biomedical Engineering Handbook: Second Edition.
Ed. Joseph D. Bronzino.
Boca Raton: CRC Press LLC, 2000

2.2. Electrode Polarization

When no DC electric current flows between an electrode and the body, the DC potential observed is only the half-cell potential. If, however, there is a DC current, the half-cell potential will be altered, this effect is commonly referred to as over-voltage. This *over voltage* generates the effect known as polarization and can result in diminished electrode performance, especially under conditions of motion, because it impedes the current flowing through the electrode into the body. Thus, for most biomedical measurements, non-polarizable electrodes (wet electrodes) are preferred to those that are polarizable (dry electrodes). However, most of the portable and consumer applications must use dry electrodes due to its reusability and low cost.

2.3. Electrode-Skin Impedance

The electrode equivalent circuit is shown in *Figure 1*. R_d and C_d represent the impedance associated with the electrode-skin interface and polarization at this interface. R_s is the series resistance associated with the type of electrode materials. E_{hc} is the half-cell potential.

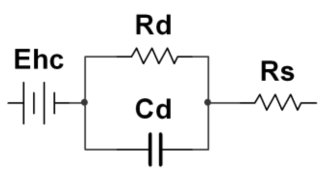

Figure 1 Equivalent circuit model for bio-potential electrode.

The electrode-skin impedance[2] is dominated by the series combination of R_s and R_d at low frequencies. But, this impedance decreases at higher frequencies due to the capacitor's effect. *Table 2* shows the typical values of R_d and C_d for some typical materials and its magnitude impedance at 1 kHz.

The electrode-skin impedance is an important issue when designing the analog front end due to the high impedances involved.

Material	**R_d**	**C_d**	**$\lvert R_d//C_d \rvert$ @ 1kHz**
Wet Ag/AgCl	350kΩ	25nF	6kΩ
Metal Plate	1.3MΩ	12nF	13kΩ
Thin Film	550MΩ	220pF	724kΩ
MEMS	650kΩ	Negligible	650kΩ

[2] Yu Mike Chi, Tzyy-Ping Jung, Gert Cauwenberghs, *Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review.* INSPEC Accession Number: 11674853

Table 2Electrode-Skin typical impedance

2.4. IEC6060-1

The IEC 60601 is a series of technical standards for the patient/wearer safety and effectiveness of medical electrical equipment, published by the International Electrotechnical Commission[3]. This standard specifies the limits of patient leakage currents and patient auxiliary currents under normal conditions and single fault conditions[4]. These current limits are important parameters in the circuit design.

The maximum DC current allowed to be sourced in the body in normal conditions has to be less than or equal to 10uA and the maximum DC current under single fault condition in the worst scenario is 50uA.

The maximum AC current allowed to be sourced in the body in normal conditions depends on the frequency. If the excitation frequency is less than or equal to 1 kHz, the maximum allowed current is $10uA_{RMS}$. If the excitation frequency (F_E) is greater than 1 kHz, the maximum current is defined by the *Equation 1*.

$$I_{AC_{MAX}} = \frac{F_E}{1000\ Hz} \cdot 10uA_{RMS}$$

Equation 1 Max AC current if FE>1 kHz.

3. SOLUTION

The impedance measurement always requires a voltage/current source and a current/voltage meter, thus DACs and ADC are common blocks in these systems. Precision voltage reference and voltage/current control loops are also essential blocks. A microcontroller is typically required to process data and obtain the real and imaginary part of the impedance values. Additionally, body worn devices are typically supplied by a unipolar battery. Finally, the BOM is critical, thus the integration of as many components as possible in a single package is very beneficial.

The ADuCM350 represents a powerful solution in this application since it is an ultralow power, integrated mixed-signal metering solution that includes a Cortex™-M3 processor and a hardware accelerator which can perform a single frequency discrete Fourier transform (DFT).

[3] http://en.wikipedia.org/wiki/IEC_60601
[4] Single fault condition: Condition in which a single means for protection against hazards is defective or a single external abnormal hazardous condition is present

To meet the IEC-60601 standards, the ADuCM350 is used with an external instrumentation amplifier (AD8226), to complete high precision absolute measurements using a 4-wire measurement technique.

The circuit in *Figure 2* solves the polarization effect because there is not DC current flowing between the electrode and the user, the capacitors C_{SIO1} and C_{ISO2} block it. The signal which is propagated into the body is an AC signal generated by the ADuCM350.

The capacitors C_{ISO3} and C_{ISO4} are DC blocking capacitors which solve the problem with the half-cell potential by blocking this DC level from the ADC, thus maintaining maximum dynamic range at all times.

C_{ISO1}, C_{ISO2}, C_{ISO3} and C_{ISO4} also ensure the DC current in normal mode and in first case of failure and AC current in first case of failure are zero because the user is isolated. Finally, the resistor R_{LIMIT} is designed to guarantee the AC current in normal operation mode is below the limit.

R_{ACCESS} symbolizes the skin-electrode contact.

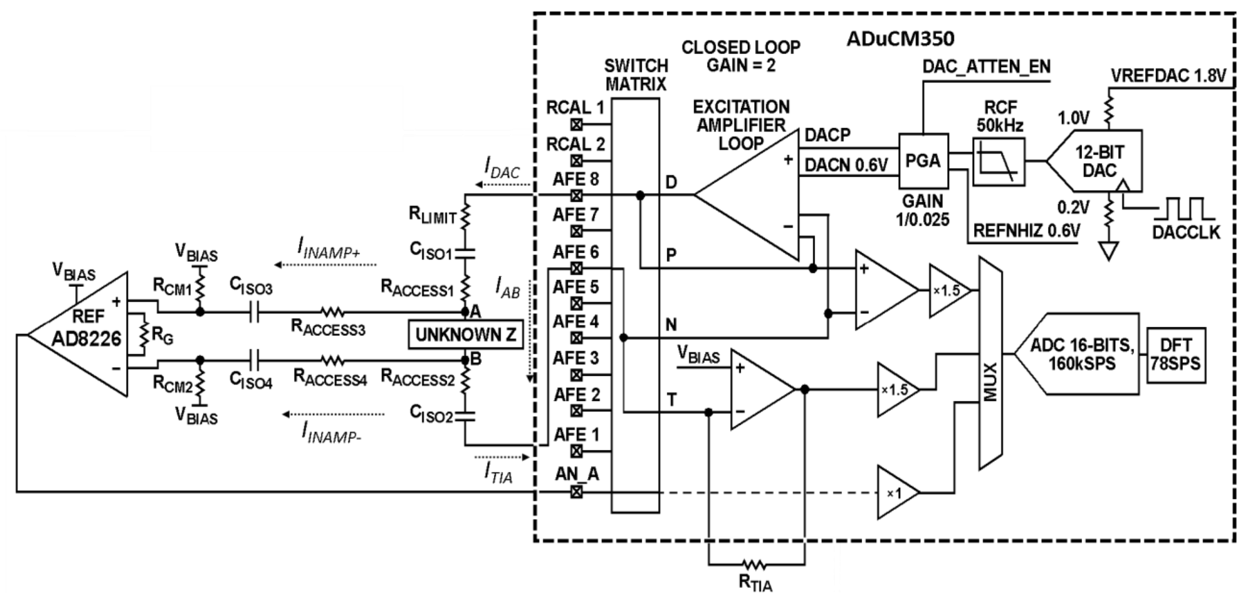

Figure 2 4-Wire isolated measurement circuit using ADuCM350 and AD8226.

3.1. Circuit Design

Equation 2, *Equation 3* and *Equation 4* describe the DAC's current (I_{DAC}), the unknown body-impedance's current (I_{AB}) and the TIA's current (I_{TIA}) relationship in the circuit shown in *Figure 2*.

The ADuCM350 measures the I_{TIA} current and the output voltage of the AD8226 to calculate the unknown body-impedance.

We want to maintain the largest value as possible for I_{TIA} to maximize the SNR measurement from the ADuCM350 TIA. This requires that I_{INAMP-} must be as small as possible according to *Equation 3*. A good rule of thumb is to make I_{INAMP-} ten times smaller than I_{TIA}. To do this $R_{ACCES4} + \frac{1}{C_{ISO4}} + R_{CM2}$ must be, at least, ten times greater than $R_{ACCES2} + \frac{1}{C_{ISO2}} + R_{TIA}$. This rule can be simplified because $R_{ACCES2} + \frac{1}{C_{ISO2}}$ is typically equal to $R_{ACCES4} + \frac{1}{C_{ISO4}}$, thus the final equation determines that R_{CM2} must be, at least, ten times greater than R_{TIA}.

$$I_{DAC} = I_{AB} + I_{INAMP+}$$

Equation 2 DAC's current

$$I_{TIA} = I_{AB} - I_{INAMP-}$$

Equation 3 Measured current by ADuCM350 TIA.

$$I_{TIA} > 10 \cdot I_{INAMP-} \rightarrow R_{CM2} > 10 \cdot R_{TIA}$$

Equation 4 R_{CM2} must be, at least, 10 times greater than R_{TIA}.

The instrumentation amplifier must measure the voltage in extremes of the unknown impedance, so, ideally, the voltage in *A* should be equal to V_{INAMP+} and the voltage in *B* should be equal to V_{INAMP-}.

Equation 4 describes V_{INAMP+}, if R_{CM1} is 10 (or more) times greater than$R_{ACCESS3} + \frac{1}{C_{ISO3}P}$, the voltage in *A* is practically equal to V_{INAMP+}.

$$V_{INAMP+} = \frac{R_{CM1}}{R_{ACCESS3} + \frac{1}{C_{ISO3}P} + R_{CM1}} \cdot A; if\ R_{CM1} > 10 \cdot \left(R_{ACCESS3} + \frac{1}{C_{ISO3}P}\right) => V_{INAMP+} = A$$

Equation 5 R_{CM1} must be, at least, 10 times greater than R_{ACCES3}+1/C_{ISO3}.

$$V_{INAMP-} = \frac{R_{CM2}}{R_{ACCESS4} + \frac{1}{C_{ISO4}P} + R_{CM2}} \cdot B; if\ R_{CM2} > 10 \cdot \left(R_{ACCESS4} + \frac{1}{C_{ISO4}P}\right) => V_{INAMP-} = B$$

Equation 6 R_{CM2} must be, at least, greater than $R_{ACCESS4}$+1/C_{ISO4}.

Hence, R_{CM1} and R_{CM2} must be as high as possible to ensure most of the current flows through the unknown impedance and the TIA. Besides, the voltage measured by the instrumentation amplifier is practically the voltage in extremes of the unknown impedance. The recommended value is 10MΩ

3.2. Mathematical Study

The circuit shown in *Figure 2* is analyzed from the mathematical point of view in order to understand its design. The explained assumptions in the previous section are applied in this analysis.

The measured current by the ADuCM350's TIA (considering I_{INAMP+} and I_{INAMP-} equal to zero) is:

$$V_{current} = -\frac{R_{TIA}}{R_{LIMIT} + R_{ACCESS1} + \frac{1}{C_{ISO1}P} + Z_{UNKNOWN} + R_{ACCESS2} + \frac{1}{C_{ISO2}P}} \cdot V_{AC_{ADuCM350}}$$

Equation 7 Current measurement carried out byADuCM350's TIA

The voltage in V_{INAMP+} (considering the voltage in *A* = V_{INAMP+}) is:

$$V_{INAMP+} = \frac{Z_{UNKNOWN} + R_{ACCESS2} + \frac{1}{C_{ISO2}P}}{R_{LIMIT} + R_{ACCESS1} + \frac{1}{C_{ISO1}P} + Z_{UNKNOWN} + R_{ACCESS2} + \frac{1}{C_{ISO2}P}} \cdot V_{AC_{ADuCM350}}$$

Equation 8 Voltage in the instrumentation amplifier's positive input

The voltage in V_{INAMP-} (considering the voltage in *B* = V_{INAMP-}) is:

$$V_{INAMP-} = \frac{R_{ACCESS2} + \frac{1}{C_{ISO2}P}}{R_{LIMIT} + R_{ACCESS1} + \frac{1}{C_{ISO1}P} + Z_{UNKNOWN} + R_{ACCESS2} + \frac{1}{C_{ISO2}P}} \cdot V_{AC_{ADuCM350}}$$

Equation 9 Voltage in the instrumentation amplifier's negative input

The measured voltage by the instrumentation is:

$$V_{Voltage} = G \cdot (V_{INAMP+} - V_{INAMP-})$$

$$V_{Voltage} = G \cdot \frac{Z_{UNKNOWN}}{R_{LIMIT} + R_{ACCESS1} + \frac{1}{C_{ISO1}P} + Z_{UNKNOWN} + R_{ACCESS2} + \frac{1}{C_{ISO2}P}} \cdot V_{AC_{ADuCM350}}$$

Equation 10 Voltage measurement carried out by the instrumentation amplifier

The unknown impedance is obtained by the division of the Vvoltage and Vcurrent:

$$\frac{V_{Voltage}}{V_{current}} = -\frac{G \cdot Z_{UNKNOWN}}{R_{TIA}} \quad \rightarrow \quad Z_{UNKNOWN} = -\frac{1}{G} \cdot \frac{V_{voltage}}{V_{current}} \cdot R_{TIA}$$

Equation 11 Body Impedance Measurement

$$|Z_{UNKNOWN}| = \frac{R_{TIA}}{G} \cdot \frac{|V_{voltage}|}{|V_{current}|}$$

Equation 12 Body Impedance Magnitude

$$Phase(Z_{UNKNOWN}) = 180 + \left(Phase\left(V_{voltage}\right) - Phase(V_{current})\right)$$

Equation 13 Body Impedance Phase

3.3. Design Limitations

This design presents some limitations when the electrode-skin impedance is close to 10MΩ at the excitation frequency. If the electrode-skin impedance is not significantly smaller than R_{CM1} and R_{CM2} (10MΩ), V_{INAMP+} cannot be considered equal to *A* and V_{INAMP-} cannot be considered equal to *B* (see *Equation 5* and *Equation 6*). Thus, the measurement accuracy is degraded. However, the electro-skin impedance is typically much smaller than 1MΩ when the excitation frequency is greater than 1 kHz (see *Table 2*).

4. VALIDATION

To prove the accuracy of this design, the system has been tested with different unknown impedances. The values of the components in *Figure 2* are listed below.

Component	Value
$R_{ACCESS1}$, $R_{ACCESS2}$, $R_{ACCESS3}$ and $R_{ACCESS4}$	220Ω
C_{ISO1}, C_{ISO2}, C_{ISO3} and C_{ISO4}	47nF
R_{CM1} and R_{CM2}	10MΩ
R_G	43kΩ
R_{LIMIT}	1kΩ
R_{TIA}	1.8kΩ

Table 3 Component values

The unknown impedances have been measured by an Agilent 4294A impedance analyzer. Results are shown in *Table 4*. The magnitude error is less than ±1% in all the tests.

Absolute phase error is less than 1 degree at 500 Hz and 5 kHz. The circuit under test presents an offset of 9 degrees in the phase measurements at 50 kHz which may be corrected by software

RESULTS							
Test 1		**Agilent 4294A**		**Body-Imp. Circuit**		**Errors**	
Theoretical value	Freq. (Hz)	Mag. (Ω)	Phase (º)	Mag. (Ω)	Phase (º)	Error (%) Mag	Abs. Error Phase
2kΩ	500	1995.22	-0.002	1989.50	-0.062	-0.286	-0.060
	5000	1995.60	-0.100	1989.37	-0.900	-0.311	-0.800
	50000	1995.13	-0.400	1982.81	-9.187	-0.617	-8.787
Test 2		**Agilent 4294A**		**Body-Imp. Circuit**		**Errors**	
Theoretical value	Freq. (Hz)	Mag. (Ω)	Phase (º)	Mag. (Ω)	Phase (º)	Error (%) Mag	Abs. Error Phase
200Ω	500	201.09	-0.006	199.687	-0.250	-0.697	-0.244
	5000	201.04	-0.008	199.812	-0.875	-0.610	-0.867
	50000	201.10	-0.020	199.250	-9.437	-0.919	-9.417
Test 3		**Agilent 4294A**		**Body-Imp. Circuit**		**Errors**	
Theoretical value	Freq. (Hz)	Mag. (Ω)	Phase (º)	Mag. (Ω)	Phase (º)	Error (%) Mag	Abs Error Phase
(2k+22nF)// 1kΩ	500	996.80	-01.77	993.500	-01.750	-0.331	0.025
	5000	862.00	-11.00	861.625	-11.875	-0.044	-0.875
	50000	671.70	-03.20	666.937	-12.300	-0.709	-9.100
Test 4		**Agilent 4294A**		**Body-Imp. Circuit**		**Errors**	
Theoretical value	Freq. (Hz)	Mag. (Ω)	Phase (º)	Mag. (Ω)	Phase (º)	Error (%) Mag	Abs Error Phase
(2k+44nF)// 1kΩ	500	991.531	-03.095	988.56	-03.000	-0.299	0.095
	5000	773	-11.000	773.19	-12.000	0.024	-1.000
	50000	668	-01.975	663.43	-11.000	-0.683	-9.025

Table 4 Test results

5. CONCLUSIONS

Designing a battery operated body worn bio-impedance measurement solution must consider low power, high SNR, electrode polarization and the IEC60601 safety requirements. The solution using the ADuCM350 and AD8226 described in *Figure 2* meets these requirements.