Application Report
SBAA202 – October 2013

Impedance Measurement with the AFE4300

Van Yang, Praveen Aroul, Kevin Wen
High Performance Analog

ABSTRACT

This article gives a brief overview of bio-impedance measurements and discusses the methodology to measure impedance with AFE4300, an analog frond end for weight and body composition measurement. The article also includes the step-by-step procedure to calibrate and measure the impedance using the AFE4300 demonstration kit and the PC application software. The measurement results of two typical bio-impedance networks are analyzed.

Contents

List of Figures

List of Tables

1 Introduction of Bio-Impedance Measurements

In biomedical engineering, bio-impedance is the response of a living organism to externally applied electric current. Bio-impedance is a measure of the opposition to the flow of that electric current through the tissues, the opposite of the electrical conductivity. The measurement of the bio-impedance of humans and animals has proved useful as a non-invasive method for measuring blood flow and body composition.

The bio-impedance model of a cell is described in Figure 1, where R_e is the extracellular resistance, C_m is the cell membrane capacitor, R_m is the cell membrane resistor, and R_i is the intracellular resistance. The bio-impedance of a cell is decided by various factors like cell size, shape, density, homogeneity, and so forth.

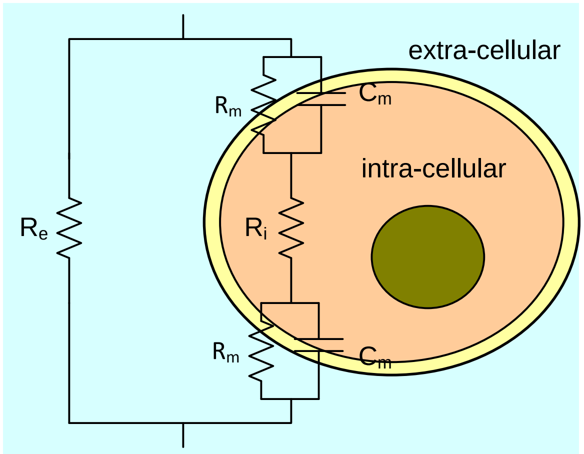

Figure 1. Cell Bio-Impedance Model

There are now four popular methods of bio-impedance analysis (BIA): single frequency BIA (SF-BIA), multi-frequency BIA (MF-BIA), segmental-BIA, and bioelectrical spectroscopy (BIS).

1.1 *Tetrapolar Single (SF-BIA) and Multi-frequency (MF-BIA) BIA*

To measure the bio-impedance, a high-frequency AC current is injected into the tissue through the drive electrodes (refer to Figure 2). The AC current causes a potential voltage difference between the two receive electrodes (refer to Figure 2). This potential voltage difference is related to the resistivity of the tissue between the voltage-sensing or receive electrodes. The equivalent resistance is defined as the ratio of the voltage difference between the two receive electrodes and the current that flows through the tissue. Having four electrodes in the tetrapolar configuration as shown in Figure 2 eliminates the inaccuracies related to the electrode impedances.

Most BIA instruments use a SF-BIA at 50 kHz which predominately measures the water outside of the cell (extracellular) and about 25% of the water inside the cells (intracellular). Various manufacturers have used hand to foot while some instruments use other locations such as hand to hand or food to foot.

MF-BIA uses different frequencies (0, 1, 5, 50, 100, 200, and 500 kHz) to evaluate FFM, TBW, ICW, and ECW. Some research shows that MF-BIA is more accurate and less biased than SF-BIA for the prediction of ECW, whereas SF-BIA, compared to MF-BIA, is more accurate and less biased for TBW in critically ill subjects.

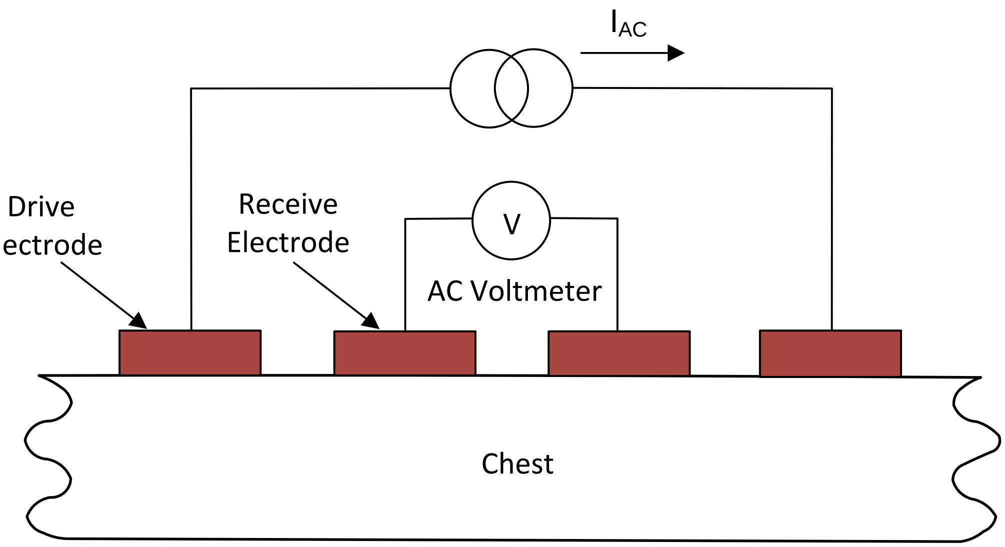

Figure 2. Bio-Impedance Measurement Model

1.2 Segmental-BIA

As the human body composition is different from hand or foot to trunk, segmental-BIA is done by adding two additional electrodes on the wrist and ankle of the opposite side (four electrodes total) or placing the two electrodes in various places to measure just the leg, arm, or torso.

1.3 Bioelectrical Spectroscopy (BIS)

In contrast to MF-BIA, BIS uses mathematical modeling and mixture equations to generate relationships between R and body fluid compartments or to predict R_0 and R_∞ and then develop empirically derived prediction equations, rather than go to mixture modeling.

2 Measuring Impedances using the AFE4300

The AFE4300 is the industry's first fully integrated analog front end for both weight and body composition measurement (BCM). AFE4300 provides some unique differentiated features that contribute to accurate bio-impedance analysis:

- Up to three tetrapolar complex impedance measurements
- Segmental-BIA using multi-channels
- Multi-frequency impedance measurement

Refer to the AFE4300 datasheet (SBAS586), for full details on device operation.

Impedance can be measured using two methods in AFE4300. The first method is Full Wave Rectifier (FWR) mode and the second method is the IQ mode. FWR mode is used to compute the magnitude of the impedance using a single frequency. This mode is also referred to as Single Frequency Bio-Impedance Analysis (SF-BIA). IQ mode is used to compute both the magnitude and the phase using, at most, four frequencies. This mode is also referred to as bioelectrical spectroscopy (BIS). With two external reference resistors, accurate magnitude and phase can be obtained using the AFE4300. The impedance measurement method using FWR mode is explained in Section 2.1, and using IQ mode is explained in Section 2.2.

Two reference resistors (Rx and Ry) are needed to perform magnitude calibration in both FWR and IQ mode. The converted voltage from the device is linear to the magnitude of the bio-impedance, as given in Equation 1:

$$\text{Mag} = m \times v + o \quad (1)$$

Where m is the slope and o is the offset. Hence, with 2 reference resistors measured accurately using a multi-meter, the slope and the offset is easily calculated.

2.1 SF-BIA Implementation using AFE4300 FWR Mode

The magnitude of bio-impedance at a specific frequency can be obtained from the AFE4300 in FWR mode. The following steps need to be taken to perform the measurement:

1. Measure the resistance of reference resistors Rx and Ry using the multimeter
2. Set the AFE4300 DAC frequency to 64 kHz
3. Measure the voltage across Rx and Ry from the AFE4300 in FWR mode
4. Calculate the slope and offset of 2-point function
5. Measure the voltage across the sample impedance network from AFE4300 in FWR mode
6. Calculate the magnitude of network in the 2-point function

Repeat steps 5 and 6 for a different sample impedance network.

For example, consider two reference resistors measured as 698.4 Ω at Rx, and 949.1 Ω at Ry. Injecting a 64-kHz frequency current and setting the data rate of the ADC to 64 SPS, the ADC codes are 9074 and 12331. So the slope of Equation 1 is (949.1 – 698.4) / (12331 – 9074) = 0.07697 and the offset is 698.4 – (0.07697 × 9074) = –0.026.

The series RC impedance network is a 549.5-Ω resistor in series with a 4% accurate 0.111-µF capacitor. In theory, the magnitude of this sample network should be 549.96 Ω and the ADC code is 7151, the magnitude of the sample network measured using the AFE4300 in FWR mode should be 0.07697 × 7151 – 0.026 = 550.37 Ω. The percentage error is –0.08% between the computed and measured impedance.

2.2 BIS Implementation using AFE4300 IQ Mode

From the ADC codes of IQ mode, the magnitude and phase can be calculated with Equation 2.

$$\text{Mag} = \sqrt{I^2 + Q^2}, \ \text{Phase} = \arctan^{-1}\left(\frac{Q}{I}\right) \tag{2}$$

The magnitude is calibrated using the two-point calibration performed using the two reference resistors. The calculation of slope and the offset from the two-point calibration using the 2 reference resistors is done only once. The phase is compensated by subtracting the phase of the reference resistor from the phase of the measured sample impedance network. The estimation of phase of the reference resistor is done for each impedance measurement. AFE4300 can be used to perform BIS measurements at up to four frequencies (8 kHz, 16 kHz, 32 kHz, and 64 kHz).

Use the following steps to perform the impedance measurement in IQ mode:

1. Measure the resistance of reference resistors Rx and Ry using a multimeter
2. Measure the I, Q voltage across Rx and Ry from AFE4300 in I/Q mode
3. Calculate the slope and offset of 2-point function for magnitude
4. Set AFE4300 DAC frequency to 8 kHz
5. Measure the I, Q voltage of the sample Impedance network from AFE4300 in I/Q mode
6. Calibrate the magnitude of the network in the 2-point function
7. Measure the I, Q voltage of Rx from AFE4300 in I/Q mode and calculate phase of Rx
8. Calculate the phase of the network and compensate the phase by subtracting the phase of the reference resistor Rx
9. Repeat Step 4 through Step 7 for 16, 32, and 64 kHz

Repeat Step 4 and 8 for a different sample impedance network.

For example, the two reference resistors remain the same. Injecting a 64-kHz frequency current and setting the data rate of the ADC to 64 SPS , the ADC code for I channel of reference resistor Rx was 7625, ADC code for Q channel for reference resistor Rx was –4096. With Equation 2, the magnitude code is 8655 and the phase is –28.24°. Considering the same series RC network mentioned in Section 2.1, the ADC code for I channel was 6153 and the ADC code for Q channel was –3649 and based on Section 2.1, the magnitude code was 7154 or 0.07697 × 7154 – 0.026 = 550.62 Ω and the phase was –30.68°. The compensated phase of the sample series RC network becomes –30.68 – (–28.24°) = –2.44°. The theoretical magnitude and phase of the sample RC network is 549.96 and –2.33°. Hence the % error for the magnitude is –0.12 % and the relative error for the phase is –0.11°error.

3 Using the AFE4300 GUI for Impedance Measurements

3.1 AFE4300 GUI Setting for Impedance Measurement

For impedance measurement using AFE4300, first, the AFE4300 registers need to be configured, second, the controls in the BCM Measurement tab need to be set, third, depending on FWR or IQ mode, the impedance can be measured at a single or multiple frequencies respectively and finally the measurement results are compared with the calculated impedance using MATLAB®. Please refer to the following detailed instructions:

Step 1: The AFE4300 registers can be configured to enable the impedance measurement and calibration on the GUI using the 3 files in the GUI installation directory. These 3 files are located in the AFE4300 EVM GUI installation directory:

- "C:\Program Files\Texas Instruments\AFE4300 Device GUI" (Windows® XP)
- "C:\Program Files(x86)\Texas Instruments\AFE4300 Device GUI" (Windows 7).

The three files are;

- AFE4300 Device GUI.ini
- Calib Const.ini
- Write Register.csv

In AFE4300 Device GUI.ini, the calibration function should be enabled, set to true, as shown in Figure 3.

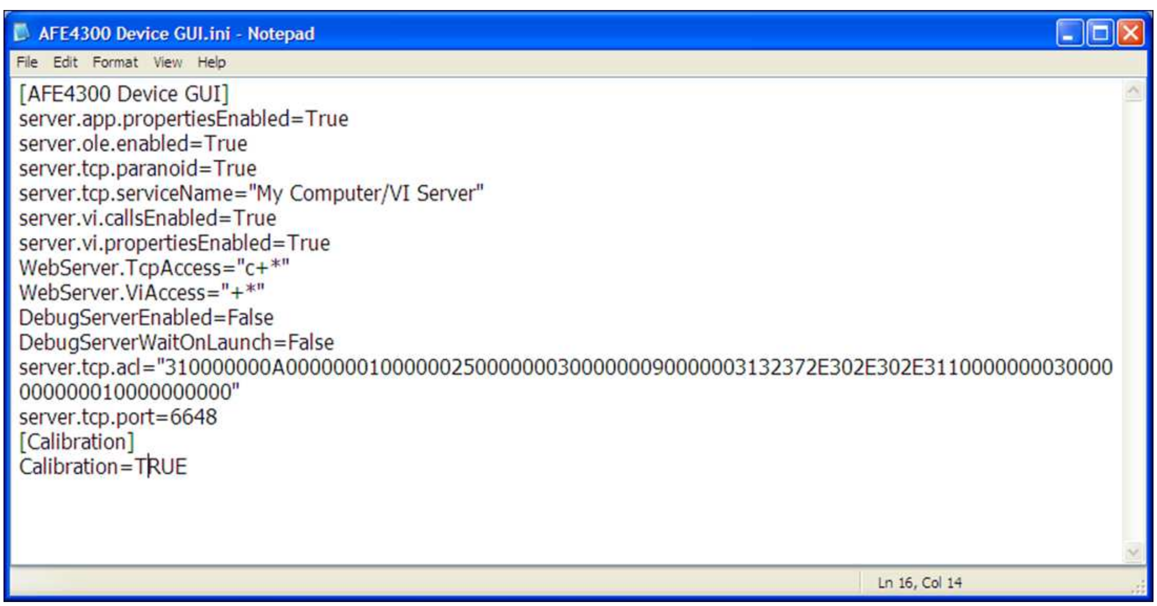

Figure 3. AFE4300 Device GUI.ini Setting

The frequency for the AFE4300 DAC is set in Calib Const.ini. For the FWR mode, a single frequency can be set. IQ mode supports 3 or 4 frequencies and these frequencies can be modified as shown in Figure 4.

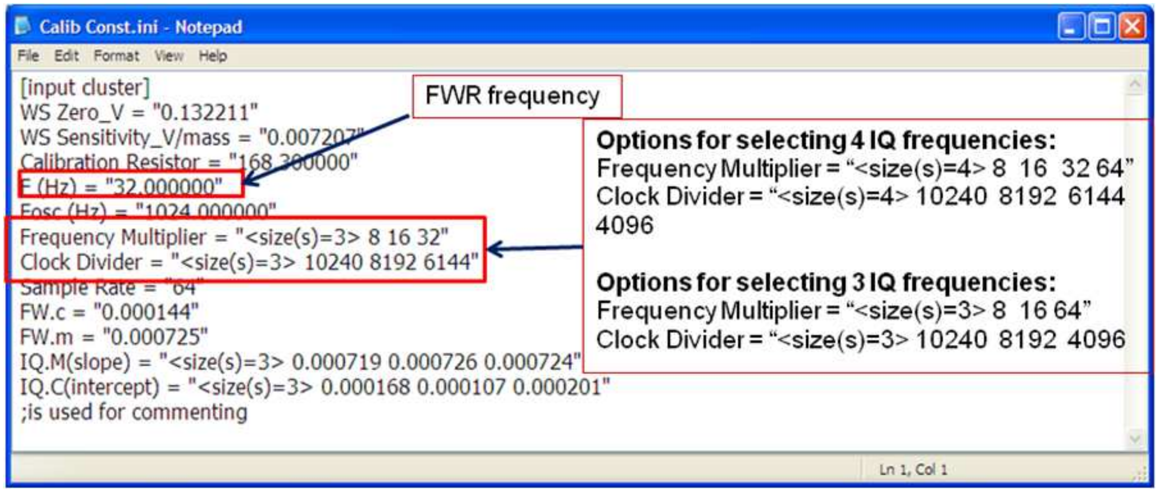

Figure 4. AFE4300 GUI Calib Const.ini Setting

There are 4 reference resistors on the AFE4300EVM,

- R56 – 700 Ohms,
- R57 – 950 Ohms,
- R58 – 100 Ohms,
- R59 – 200 Ohms.

Modify the registers in the Write Registers.csv to choose the IOUT and VSENSE reference channels for the two reference resistors for calibration in FWR mode, as shown in Figure 5.

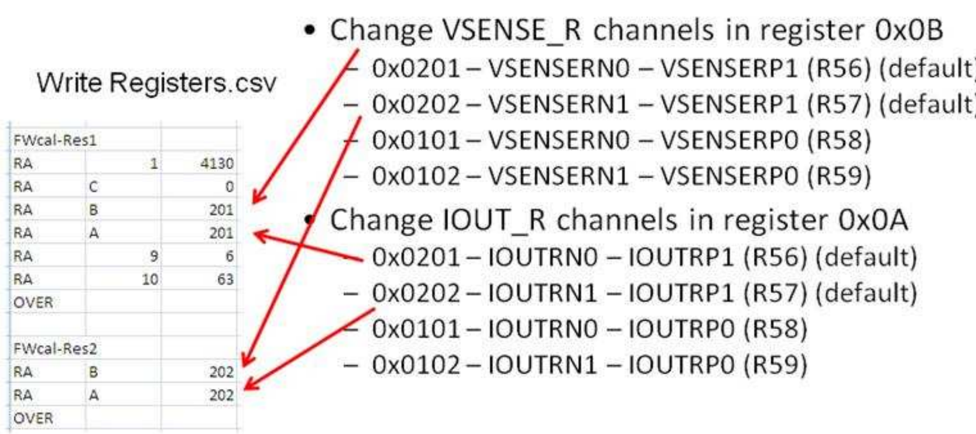

Figure 5. Reference Resistors Setting

The AFE4300 can support up to 3 tetrapolar channels for the impedance measurement. So, before the impedance measurement in FWR mode, select the IOUT and VSENSE channels in the Write Registers.csv, as shown in Figure 6.

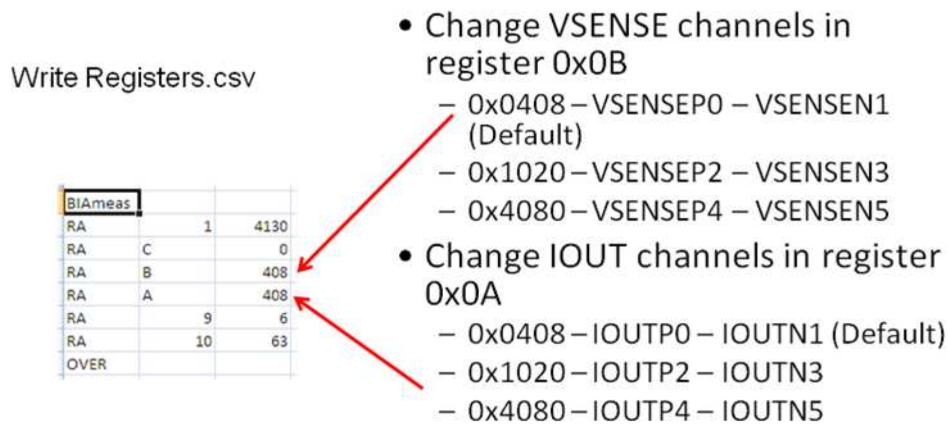

Figure 6. Channel Setting

For the IQ mode, IQ mode should be enabled, and the IOUT and VSENSE reference channels for the two reference resistors for calibration should be selected, as shown in Figure 7.

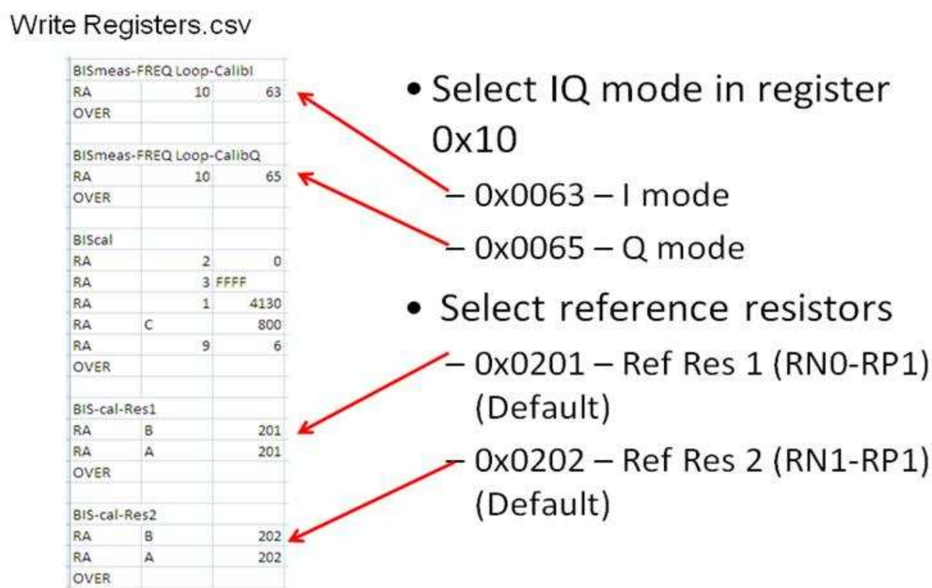

Figure 7. IQ Mode Enable and EVM Reference Resistors Notification

For the IQ mode, the IOUT and VSENSE channels for the impedance measurement and the IOUT and VSENSE channels for the phase reference resistor should be selected, as shown in Figure 8.

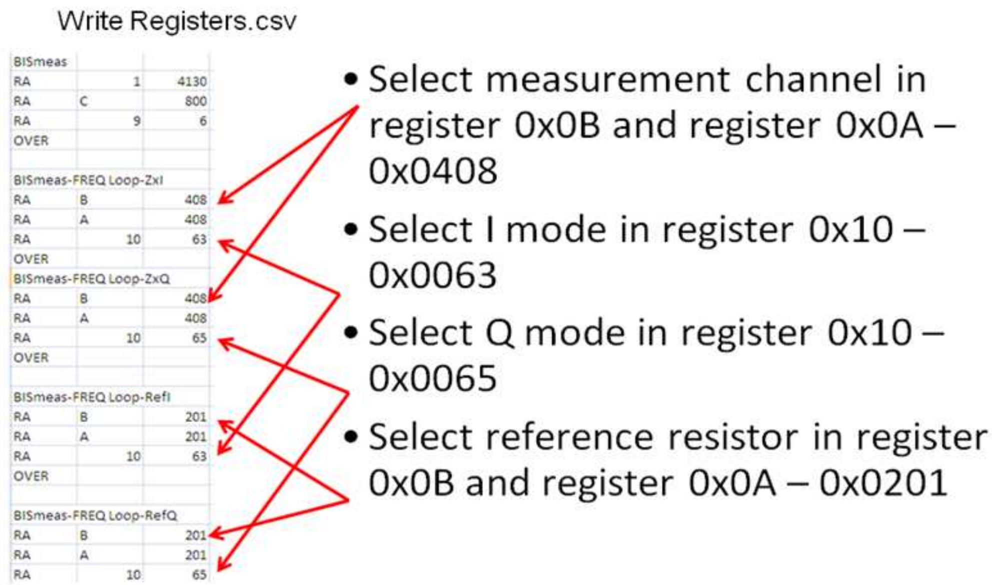

Figure 8. IQ Mode Phase Reference Resistor Setting

Step 2: After the 3 GUI setting files have been modified, connect the EVM to the PC and start the AFE4300 Device GUI.

For the impedance measurement in FWR mode, there are 5 steps to set the controls to measure the magnitude of the impedance network. Enter the value of the reference resistors measured using the multimeter and click the **CALIBRATE FWR** button to compute the slope and offset. Choose the *BCM Mode* to *FWR Mode* then click the **MEASURE BCM** button to start the measurement process. The magnitude of the sample network is displayed in the *FWR Measurement Intermediate Outputs*, as shown in Figure 9

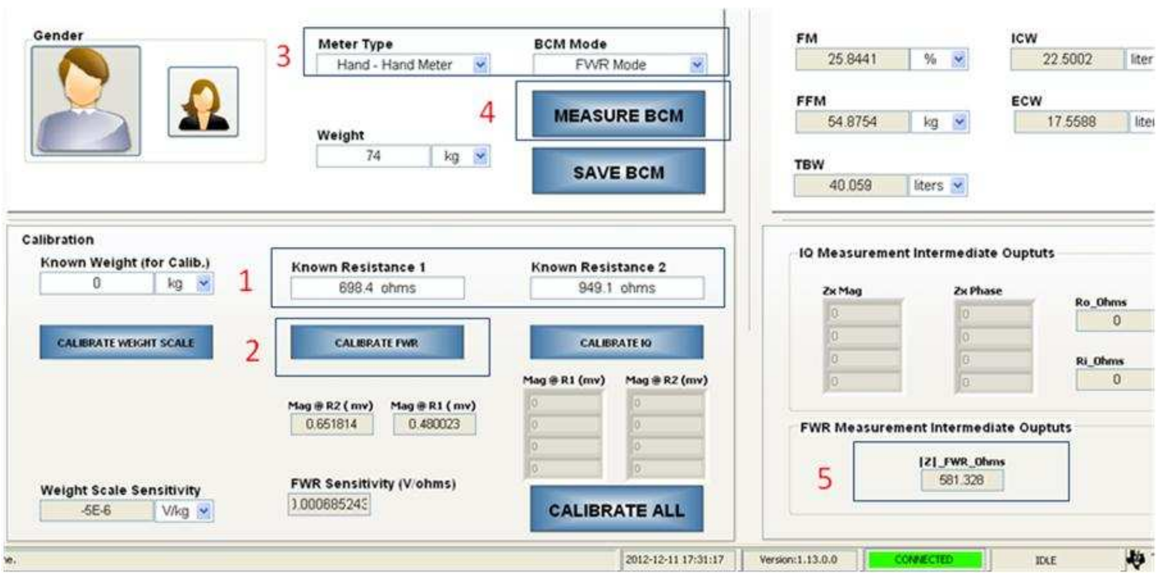

Figure 9. Impedance Measurement in FWR Mode with the AFE4300 GUI

Follow the steps shown in Figure 10 to perform the measurement in IQ mode with the GUI. View the calibrated magnitude and the compensated phase under the *IQ Measurement Intermediate Outputs* section.

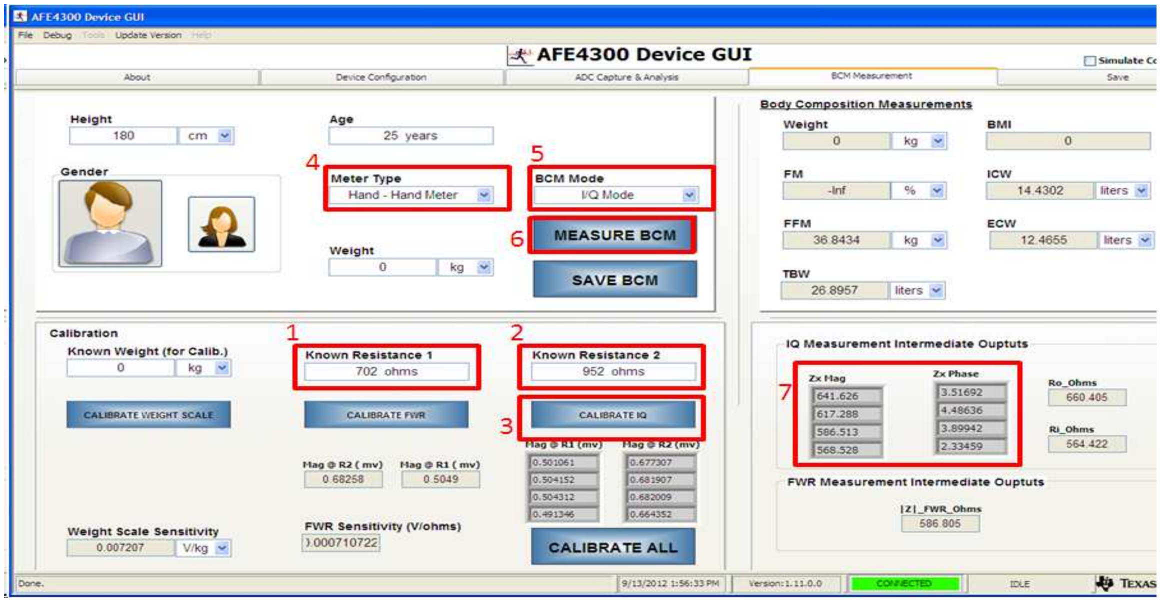

Figure 10. IQ Mode Impedance Measurement with the AFE4300 GUI

3.2 Test Results of Impedance Measurement of Sample Networks

3.2.1 Test Networks

Three sample networks were tested. The first network is resistive (500 Ω and 1005 Ω), the second network is a series RC network, and the third network is a parallel RC network in series with a series RC network. The resistors values were measured using a multi-meter, and the accuracy of the capacitor was 4%. The three networks are shown in Figure 11.

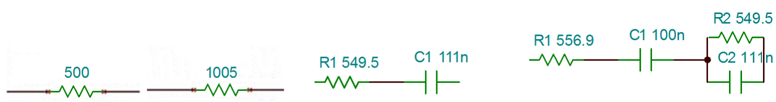

Figure 11. Three Sample Networks

The impedance of the series RC network is provided in Equation 3.

$$Z = R1 - \frac{j}{\omega C_1} \tag{3}$$

The impedance of second complex network is presented in Equation 4.

$$Z = R1 - \frac{j}{\omega C1} + \frac{R2}{\left(1 + j\omega R_2 C_2\right)} \tag{4}$$

3.2.2 Test Results of Impedance Measurement in FWR Mode

For the series RC network, the impedance measurement was performed for 5 iterations and the data are presented in Table 1. In the table, Mag_M is the impedance value measured with the AFE4300 GUI, Mag_R is the impedance calculated in MATLAB, and the Error of Mag is the relative error.

Table 1. Serial RC Network Impedance Test Results in FWR Mode

	Frequency	Mag_M	Mag_R	Error of Mag
1	8 kHz	581.33	577.99	–0.58%
	16 kHz	557.81	556.76	–0.19%
	32 kHz	551.67	551.32	–0.06%
	64 kHz	550.37	549.96	–0.08%
2	8 kHz	581.32	577.99	–0.58%
	16 kHz	557.8	556.76	–0.19%
	32 kHz	551.66	551.32	–0.06%
	64 kHz	550.36	549.96	–0.07%
3	8 kHz	581.32	577.99	–0.58%
	16 kHz	557.8	556.76	–0.19%
	32 kHz	551.66	551.32	–0.06%
	64 kHz	550.36	549.96	–0.07%
4	8 kHz	581.35	577.99	–0.58%
	16 kHz	557.8	556.76	–0.19%
	32 kHz	551.65	551.32	–0.06%
	64 kHz	550.35	549.96	–0.07%
5	8 kHz	581.31	577.99	–0.57%
	16 kHz	557.82	556.76	–0.19%
	32 kHz	551.67	551.32	–0.06%
	64 kHz	550.37	549.96	–0.08%

The complex RC network test results in FWR mode is shown in Table 2.

Table 2. Complex Network Impedance Measurement in FWR Mode

	Frequency	Mag_M	Mag_R	Error of Mag
1	8 kHz	722.02	708.82	–1.86%
	16 kHz	607.71	601.18	–1.09%
	32 kHz	571.11	568.69	–0.42%
	64 kHz	561.5	560.11	–0.25%
2	8 kHz	722.14	708.82	–1.88%
	16 kHz	607.69	601.18	–1.08%
	32 kHz	571.09	568.69	–0.42%
	64 kHz	561.44	560.11	–0.24%
3	8 kHz	722.22	708.82	–1.89%
	16 kHz	607.71	601.18	–1.09%
	32 kHz	571.08	568.69	–0.42%
	64 kHz	561.44	560.11	–0.24%
4	8 kHz	722.23	708.82	–1.89%
	16 kHz	607.73	601.18	–1.09%
	32 kHz	571.08	568.69	–0.42%
	64 kHz	561.44	560.11	–0.24%
5	8 kHz	722.26	708.82	–1.90%
	16 kHz	607.72	601.18	–1.09%
	32 kHz	571.1	568.69	–0.42%
	64 kHz	561.45	560.11	–0.24%

3.2.3 Test Results of Impedance Measurement in IQ Mode

The 2 sample RC networks described earlier were measured in IQ mode. The test results include the measured phase with the AFE4300 GUI in Phase_M, the MATLAB calculate phase Phase_R, and the relative error of phase, Error of Phase. The series network test results in IQ mode are shown in Table 3 and the complex network results are shown in Table 4.

Table 3. Serial RC Network Impedance Test Results in IQ Mode

	Frequency	Mag_M	Phase_M	Mag_R	Phase_R	Error of Mag	Error of Phase
1	8 kHz	586.35	–18.57	577.99	–18.06	–1.45%	0.51
	16 kHz	559.34	–9.63	556.76	–9.26	–0.46%	0.37
	32 kHz	550.35	–4.87	551.32	–4.66	0.18%	0.2
	64 kHz	550.65	–2.43	549.96	–2.33	–0.13%	0.09
2	8 kHz	587.87	–18.53	577.99	–18.06	–1.71%	0.47
	16 kHz	560.34	–9.62	556.76	–9.26	–0.64%	0.35
	32 kHz	552	–4.86	551.32	–4.66	–0.12%	0.2
	64 kHz	550.62	–2.44	549.96	–2.33	–0.12%	0.1
3	8 kHz	583.38	–18.66	577.99	–18.06	–0.93%	0.59
	16 kHz	561.11	–9.61	556.76	–9.26	–0.78%	0.35
	32 kHz	548.14	–4.88	551.32	–4.66	0.58%	0.22
	64 kHz	555.63	–2.4	549.96	–2.33	–1.03%	0.06
4	8 kHz	587.14	–18.56	577.99	–18.06	–1.58%	0.5
	16 kHz	559.32	–9.64	556.76	–9.26	–0.46%	0.38
	32 kHz	555.33	–4.81	551.32	–4.66	–0.73%	0.15
	64 kHz	550.55	–2.44	549.96	–2.33	–0.11%	0.1
5	8 kHz	589.42	–18.47	577.99	–18.06	–1.98%	0.41
	16 kHz	561.09	–9.62	556.76	–9.26	–0.78%	0.35
	32 kHz	555.32	–4.81	551.32	–4.66	–0.72%	0.15
	64 kHz	550.56	–2.44	549.96	–2.33	–0.11%	0.1

Table 4. Complex Network Impedance Measurement in IQ Mode

	Frequency	Mag_M	Phase_M	Mag_R	Phase_R	Error of Mag	Error of Phase
1	8 kHz	726.02	–31.05	708.82	–30.61	–2.43%	0.44
	16 kHz	607.87	–18.69	601.18	–18.1	–1.11%	0.59
	32 kHz	568	–9.95	568.69	–9.54	0.12%	0.42
	64 kHz	561.54	–5.05	560.11	–4.84	–0.26%	0.21
2	8 kHz	724.32	–31.14	708.82	–30.61	–2.19%	0.53
	16 kHz	608.71	–18.67	601.18	–18.1	–1.25%	0.58
	32 kHz	574.89	–9.84	568.69	–9.54	–1.09%	0.3
	64 kHz	566.7	–5.00	560.11	–4.84	–1.18%	0.17
3	8 kHz	731.97	–30.85	708.82	–30.61	–3.27%	0.24
	16 kHz	610.31	–18.66	601.18	–18.1	–1.52%	0.56
	32 kHz	567.84	–9.97	568.69	–9.54	0.15%	0.43
	64 kHz	566.51	–5.01	560.11	–4.84	–1.14%	0.17
4	8 kHz	731.07	–30.87	708.82	–30.61	–3.14%	0.26
	16 kHz	606.15	–18.79	601.18	–18.1	–0.83%	0.69
	32 kHz	570.05	–9.91	568.69	–9.54	–0.24%	0.37
	64 kHz	561.61	–5.05	560.11	–4.84	–0.27%	0.21

Table 4. Complex Network Impedance Measurement in IQ Mode (continued)

	Frequency	Mag_M	Phase_M	Mag_R	Phase_R	Error of Mag	Error of Phase
5	8 kHz	724.31	–31.11	708.82	–30.61	–2.19%	0.5
	16 kHz	614.34	–18.51	601.18	–18.1	–2.19%	0.41
	32 kHz	568.11	–9.95	568.69	–9.54	0.10%	0.41
	64 kHz	561.7	–5.04	560.11	–4.84	–0.28%	0.21

4 Summary

In this report, the methodology for measuring impedance using the AFE4300 in FWR mode and IQ mode has been explained. A demonstration of how to measure the impedance with the AFE4300EVM-PDK and the PC application software is given. The test results of two typical bio-impedance networks with theoretical values are analyzed. The results show the accuracy of the impedance measurement solution using the multi-frequency and multi-channel feature of the AFE4300. The accuracy of the magnitude measurement in FWR mode is 1.89%. The accuracy of the magnitude and phase of the IQ measurements are 3.27% and 0.69 degrees, respectively.

5 References

1. Bioimpedance from Wikipedia, http://en.wikipedia.org/wiki/Bioimpedance
2. *AFE4300 datasheet*, SBAS586

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as “components”) are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI’s terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers’ products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers’ products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI’s goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or “enhanced plastic” are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have ***not*** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products		**Applications**	
Audio	www.ti.com/audio	Automotive and Transportation	www.ti.com/automotive
Amplifiers	amplifier.ti.com	Communications and Telecom	www.ti.com/communications
Data Converters	dataconverter.ti.com	Computers and Peripherals	www.ti.com/computers
DLP® Products	www.dlp.com	Consumer Electronics	www.ti.com/consumer-apps
DSP	dsp.ti.com	Energy and Lighting	www.ti.com/energy
Clocks and Timers	www.ti.com/clocks	Industrial	www.ti.com/industrial
Interface	interface.ti.com	Medical	www.ti.com/medical
Logic	logic.ti.com	Security	www.ti.com/security
Power Mgmt	power.ti.com	Space, Avionics and Defense	www.ti.com/space-avionics-defense
Microcontrollers	microcontroller.ti.com	Video and Imaging	www.ti.com/video
RFID	www.ti-rfid.com		
OMAP Applications Processors	www.ti.com/omap	**TI E2E Community**	e2e.ti.com
Wireless Connectivity	www.ti.com/wirelessconnectivity		

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265