

Wearable Electronic Devices Monitor Vital Signs, Activity Level, and More

Health Monitoring Is Going Wearable

By Jan-Hein Broeders

When I was a little boy, my mom always made sure that I had enough change to make a phone call in case of emergency. Twenty years later, mobile phones allowed us to make calls at any time and place. After another 20 years of innovation, the phone is no longer the key feature of our smart devices, which can take beautiful pictures, stream audio and video, provide access to a wide variety of services—and are now becoming our personal trainers. The devices, loaded with sensors or connected to bodily worn sensors, monitor day-to-day activity and personal health. An increasing awareness of our health has fueled interest in measuring vital parameters—such as heart rate, temperature, oxygen saturation, blood pressure, activity level, and calories burned—and following their daily trends.

Now, a universal sensor front end with multiple sensors can monitor these parameters. The biggest challenges are to minimize size and maximize battery lifetime. This article discusses solutions for the rapidly growing market for wearable electronics.

The Most Important Vital Sign

Without a heartbeat we would be in serious trouble, so pulse or heart rate is by far the most important parameter to be monitored. In addition to the number of beats per minute, we want to check the behavior of the heart as a function of activity. The rhythm is also important, as rapidly changing heart rates are a sign of cardiac disease.

Monitoring heart rate and heart activity is classically done by measuring biopotential with an electrocardiogram (ECG). Electrodes connected to the body measure signals caused by electric activity in the cardiac tissue. This principle is used in professional diagnostic systems, where up to 10 electrodes

can be connected to the chest and limbs. ECGs provide detailed information regarding the various components (P-, QRS-, and T-wave) of one heartbeat.

Single-lead ECGs are more common in the sports world, with a two-electrode chest strap measuring heart activity. ECG waveforms can be detected, but most systems just measure heart rate. These straps are uncomfortable, so the sports and wellness industry is looking for alternatives, such as integrating the electrodes into a sport shirt. The AD8232 single-lead heart rate monitor front end, shown in Figure 1, was developed for this kind of low-power wearable application. It includes an instrumentation amplifier with a gain of 100 V/V and a high-pass filter to block the offset voltage generated by the half-cell potential of the electrodes on the skin. An output buffer and low-pass filter reject the high-frequency component generated by muscle activity (EMG signals). This low-power front end, which draws 170 μ A, can be used with the ADuCM350 16-bit meter-on-a-chip to perform high-performance, single-lead ECG measurements.

New Method for Measuring Heart Rate

A new trend for measuring heart rate is the photoplethysmogram (PPG), an optical technique that retrieves cardiac information without measuring the biopotential. PPG has mainly been used to measure blood oxygen saturation (SpO₂), but can provide cardiac information without a biopotential measurement. With PPG technology, heart-rate monitors can be integrated in wearable devices such as wristwatches or bracelets. This is not possible with biopotential systems due to the tiny signal levels.

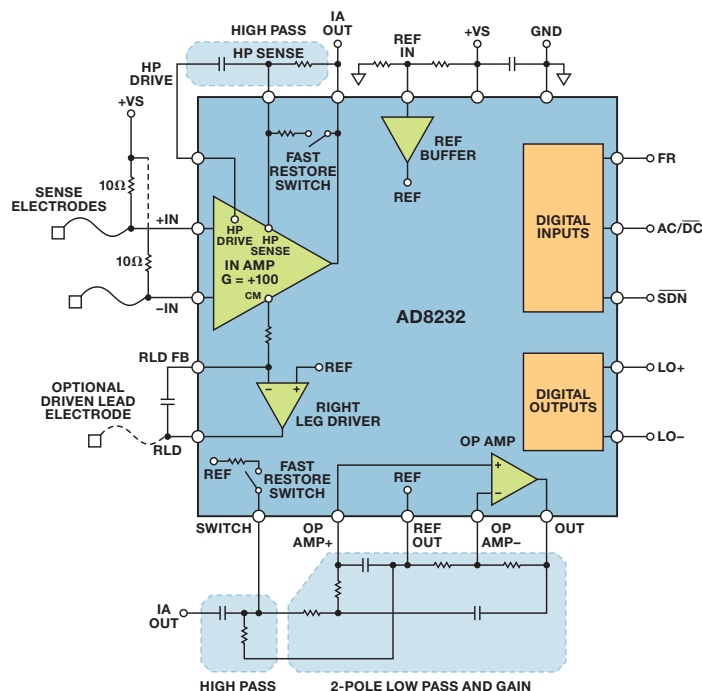


Figure 1. AD8232 single-lead ECG front end.

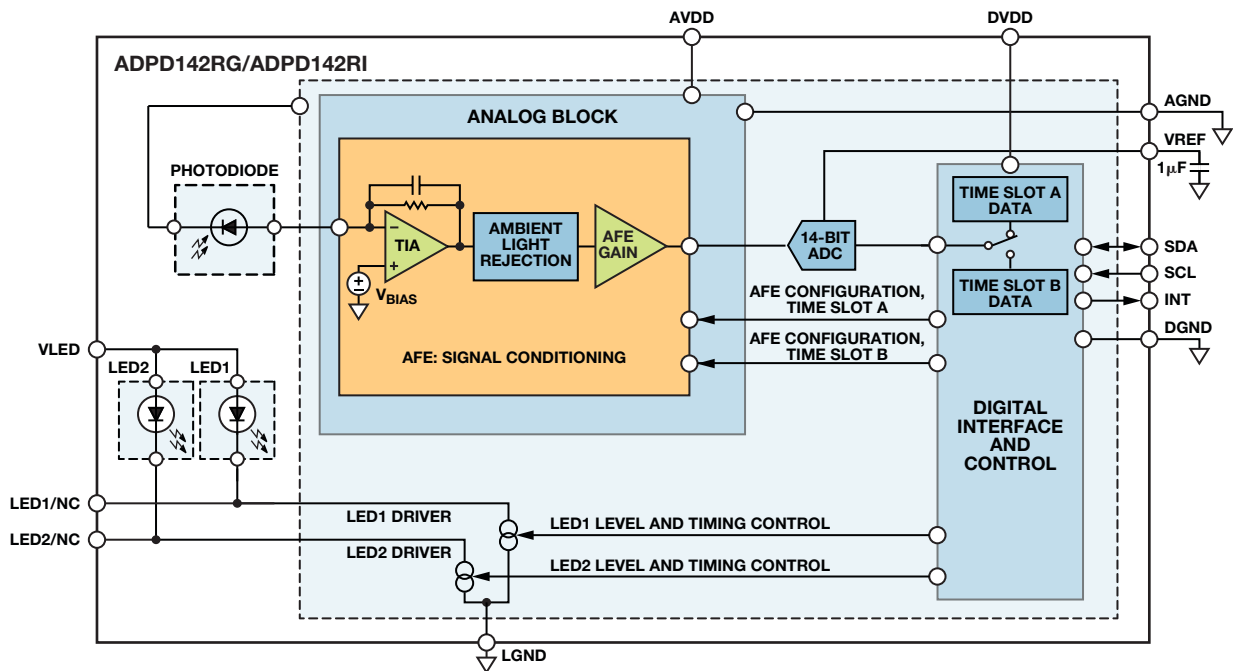


Figure 2. ADPD142 optical module.

In optical systems, light is transmitted through the surface of the skin. Light absorbed by the red blood cells is measured with a photosensor. As the heart beats, the changing blood volume scatters the amount of light received. When measured on a finger or earlobe, where considerable arterial blood is available, a red or infrared light source provides the best accuracy. Arteries are rarely located on top of the wrist, however, so with wrist worn devices, pulsatile components must be detected from veins and capillaries just under the surface of the skin, making green light better.

The ADPD142 optical module, shown in Figure 2, features a complete photometric front end, with integrated photosensor, current sources, and LEDs. Designed for reflective measurement, it can be used to implement a PPG measurement. All components are mounted in a small module.

Challenges with Optical VSM

The main challenges for measuring PPG on a wrist-worn device are due to ambient light and motion-generated artifacts. The Sun, which generates dc errors, is relatively easy to cancel out, but light from fluorescent and energy-saving lamps carry frequency components that cause ac errors. The analog front end uses two structures to reject interferers from dc to 100 kHz. After the analog signal conditioning, a 14-bit, successive-approximation analog-to-digital converter (ADC) digitizes the signal, which is transmitted via an I²C interface to a microcontroller for final post processing.

A synchronized transmit path is integrated in parallel with the optical receiver. Its independent current sources can drive two separate LEDs with current levels programmable up to 250 mA. The LED currents are pulsed, with pulse lengths in the microsecond range, so the average power dissipation is kept low to maximize battery lifetime.

The LED driving circuit is dynamic and configurable on-the-fly, making it independent of environmental conditions such as ambient light, the tint of the wearer's skin and hair, or sweat between the sensor and the skin that would otherwise

decrease sensitivity. The excitation LEDs can be configured easily to build an autoadaptive system. All timing and synchronization is handled by the analog front end, so no overhead is required from the system processor.

Two versions of the ADPD142 are available: the ADPD142RG integrates red and green LEDs to support optical heart-rate monitoring; and the ADPD142RI integrates red and infrared LEDs for oxygen saturation (SpO₂) measurement.

Influence of Motion

Motion also disturbs optical systems. When optical heart-rate monitors are used for sleep studies, this may not be an issue, but sport watches and bracelets worn during exercise have a hard time cancelling out motion artifacts. Motion between the optical sensors (LED and photodetector) and the skin will decrease the sensitivity of the optical signal. In addition, the frequency components of the motion might be seen as a heart-rate measurement, so the motion must be measured and compensated. The tighter the device is attached to the body, the lower the impact, but it is nearly impossible to cancel this out mechanically.

Various methods are used to measure motion. One is optical, using multiple LED wavelengths. The common signals indicate motion, while the differential signals detect the heart rate. It's better to use a real motion sensor, however. Not only will this allow accurate measurement of motion applied to the wearable device, but it can also be used for additional features, such as tracking activity, counting steps, or starting an application when a certain g-force is detected.

The ADXL362 micropower, 3-axis MEMS (microelectromechanical system) accelerometer is ideal for sensing motion in battery-operated wearable applications. Its 12-bit ADC converts acceleration into a digital signal with 1-mg resolution. The power consumption dynamically scales with the sampling rate, and is only 1.8 µA with a 100-Hz output data rate and 3.0 µA at 400 Hz. These higher data rates are useful for user interface, such as tap/double-tap detection.

For starting an application when motion is detected, high-speed sampling is not needed, so that the data rate can be reduced to 6 Hz, resulting in an average power consumption of 300 nA. This makes this sensor attractive for low-power applications and implantable devices, in which batteries cannot be replaced easily. The ADXL362 is available in a 3.0-mm × 3.25-mm package. Figure 3 shows the supply current vs. output data rate for several supply voltages.

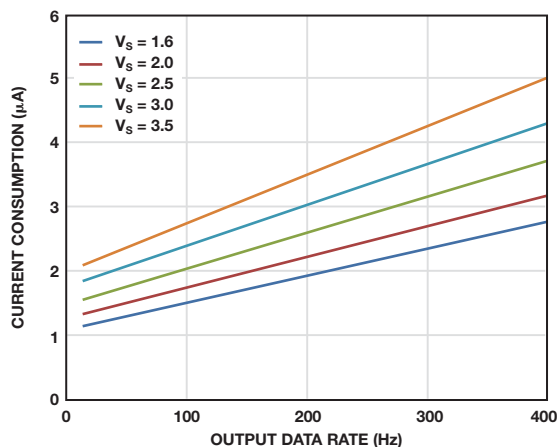


Figure 3. ADXL362 supply current as function of the output data rate.

Connecting the Sensors in the System

The heart of the system that connects all these sensors, runs the required software, and stores, displays, or transmits the results is the ADuCM350 mixed-signal meter-on-a-chip, which integrates a high-performance analog front end (AFE) with a 16-MHz ARM® Cortex®-M3 processor core, as shown in Figure 4. The flexibility of the AFE and rich feature set of the microprocessor make this chip ideal for portable and wearable applications. The configurable AFE allows it to be used with nearly any sensor, and its programmable waveform

generator powers analog sensors with ac or dc signals. The high-performance receive signal chain conditions sensor signals and converts them to digital with a true 16-bit, 160-kSPS ADC, which features ±1-LSB max INL and DNL, and no missing codes. It can be used with any type of input signal, including voltage, current, potentiostat, photocurrent, and complex impedance.

The AFE can be operated in standalone mode without involvement of the Cortex-M3 processor. A programmable sequencer controls the measurement engine, with results stored into memory via DMA. Before starting a measurement, a calibration routine can be performed to correct offset and drift errors in the transmit-and-receive signal chains. For complex impedance measurements such as blood glucose, body mass index (BMI), or tissue discrimination applications, a built-in DSP accelerator provides a 2048-point, single-frequency discrete Fourier transform (DFT) without involvement of the M3 processor. These high-performance AFE features make the ADuCM350 unique vs. other integrated solutions.

The Cortex processor supports various communication ports including I²S, USB, MIPI, and an LCD display driver (static). In addition, it includes flash memory, SRAM, and EEPROM, and supports five different power modes to maximize battery life.

Designed for use with ultralow-power sensors, the ADuCM350 is limited to low-speed devices. Applications that require more processing power could use M3 cores that operate up to 80 MHz or Cortex-M4 processor cores.

What About Power?

Power is always a critical factor in portable and wearable devices. The devices described in this article are designed for high performance, small size, and low power, but integrating everything, including the battery, in a small package is still a challenge. Despite new battery technologies that bring more capacity per mm³, the battery is still large compared to the electronics.

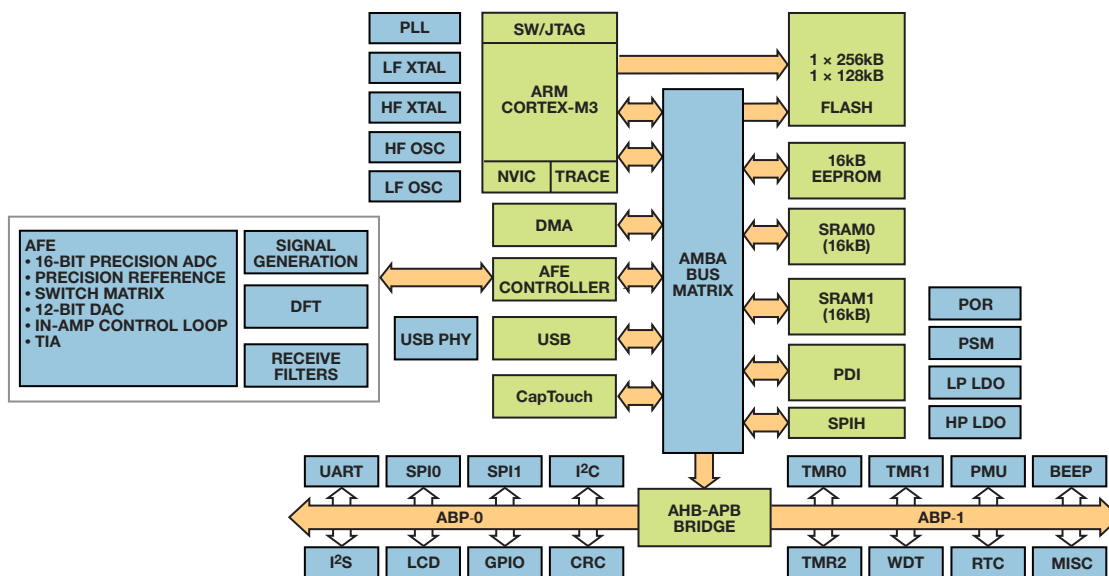


Figure 4. Cortex-M3 with integrated AFE.

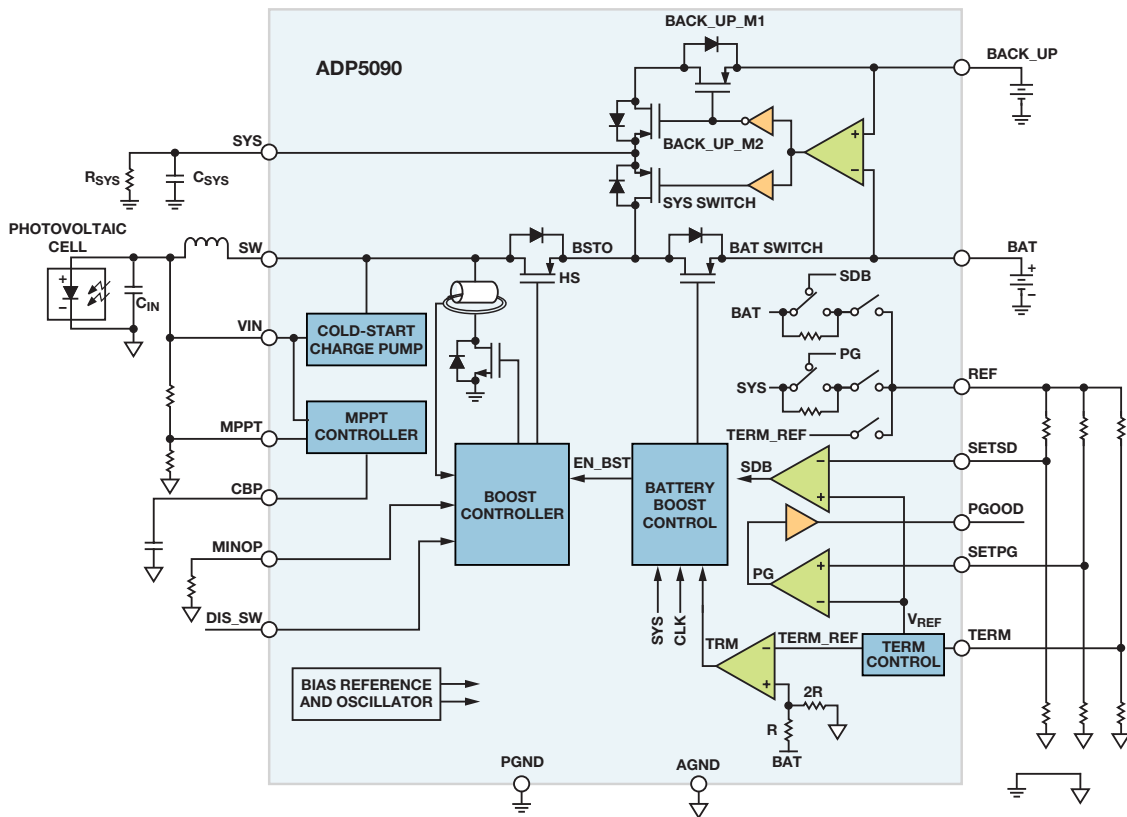


Figure 5. ADP5090 energy harvester.

Energy harvesting can reduce battery size and extend battery life. Various technologies are used to harvest energy, including thermoelectric, piezoelectric, electromagnetic, and photovoltaic, with light and heat being the most appropriate for wearable devices. The sensors usually don't provide a lot of output power, so every joule generated should be caught and used. The ADP5090 ultralow-power boost regulator, shown in Figure 5, bridges the gap between harvester and battery. This efficient switch-mode power supply boosts input voltages from as low as 100 mV up to 3 V. During a cold start, with the battery completely discharged, a 380-mV minimum input voltage is required, but in normal operation, where either the battery is not completely drawn down or some energy is left in the super capacitor, any input signal down to 100 mV can be converted to a higher potential and stored for later use.

Housed in a tiny 3-mm × 3-mm package, the chip is programmable for use with various harvester sensors. It draws 250-nA maximum quiescent current and works with almost any battery technology from Li-Ion to thin-film batteries and super capacitors. Integrated protection circuits ensure safe operation.

Conclusion

This article describes some low-power products for wearable and personal health applications, but this fast growing market is changing rapidly. ADI technology can convert challenging problems into complete products and turnkey solutions. Watch for more to come.

References

www.analog.com/healthcare

Bioimpedance Circuit Design Challenges for Body-Worn Systems

By José Carlos Conchell

Introduction

Wearable devices for vital-sign monitoring (VSM) are transforming the healthcare industry, allowing us to monitor our vital signs and activity anytime, anywhere. The most relevant information about some of these key parameters can be obtained by measuring body impedance.

To be effective, wearable devices must be small, low cost, and low power. In addition, measuring bioimpedance entails challenges related to the use of dry electrodes and safety requirements. This article provides some solutions to these issues.

Electrode Half-Cell Potential

The electrode is an electrical transducer that makes contact between an electronic circuit and a nonmetallic object such as human skin. This interaction produces a voltage, known as the half-cell potential, which reduces the dynamic range of the ADC. The half-cell potential varies with the electrode material, as shown in Table 1.

Table 1. Half-Cell Potentials for Common Materials

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

Electrode Polarization

When no current flows through the electrode, the half-cell potential is observed. The measured voltage increases when dc current flows. This overvoltage impedes current flow, polarizing the electrode, and diminishing its performance, especially under conditions of motion. For most biomedical measurements, nonpolarizable (wet) electrodes are preferred over polarizable (dry) electrodes, but portable and consumer devices typically use dry electrodes due to their low cost and reusability.

Electrode-Skin Impedance

Figure 1 shows an equivalent circuit of the electrode. 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, and E_{hc} is the half-cell potential.

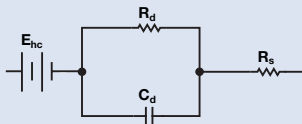


Figure 1. Equivalent circuit model for biopotential electrode.

The electrode-skin impedance is important when designing the analog front end due to the high impedances involved. Dominated by the series combination of R_s and R_d at low frequencies, the impedance decreases to R_d at high frequencies due to the capacitor's effect. Table 2 shows typical values for R_d , C_d , and the impedance at 1 kHz.

Table 2. Typical Electrode-Skin Impedance

Material	R_d	C_d	$ R_d/C_d @ 1 \text{ kHz}$
Wet Ag/AgCl	350 k Ω	25 nF	6 k Ω
Metal Plate	1.3 M Ω	12 nF	13 k Ω
Thin Film	550 M Ω	220 pF	724 k Ω
MEMS	650 k Ω	Negligible	650 k Ω

IEC 60601

IEC 60601 is a series of technical standards for the safety and effectiveness of medical electrical equipment published by the International Electrotechnical Commission. It specifies 10 μA maximum dc-leakage current through the body under normal conditions and 50 μA maximum under worst-case, single-fault conditions. The maximum ac-leakage current depends on the excitation frequency. If the frequency (f_E) is less than or equal to 1 kHz, the maximum allowed current is 10 μA rms. If the frequency is greater than 1 kHz, the maximum allowed current is $\frac{f_E}{1000 \text{ Hz}} \times 10 \mu\text{A}$ rms. These patient current limits are important circuit design parameters.

Circuit Design Solution

The impedance measurement requires a voltage/current source and a current/voltage meter, so DACs and ADCs are commonly used. A precision voltage reference and voltage/current control loops are essential, and a microcontroller is typically required to process data and obtain the real and imaginary parts of the impedance. Additionally, wearable devices are typically powered by a unipolar battery. Finally, integration of as many components as possible in a single package is very beneficial. The ADuCM350 ultralow-power, integrated, mixed-signal meter-on-a-chip includes a Cortex-M3 processor and a hardware accelerator that can perform a single-frequency discrete Fourier transform (DFT), making it a powerful solution for wearable devices.

To meet IEC 60601 standards, the ADuCM350 is used with the AD8226 instrumentation amplifier to make high-precision measurements using a 4-wire technique, as shown in Figure 2. Capacitors C_{SIO1} and C_{SIO2} block dc current flow between the electrode and the user, eliminating the polarization effect. An ac signal generated by the ADuCM350 is propagated into the body.

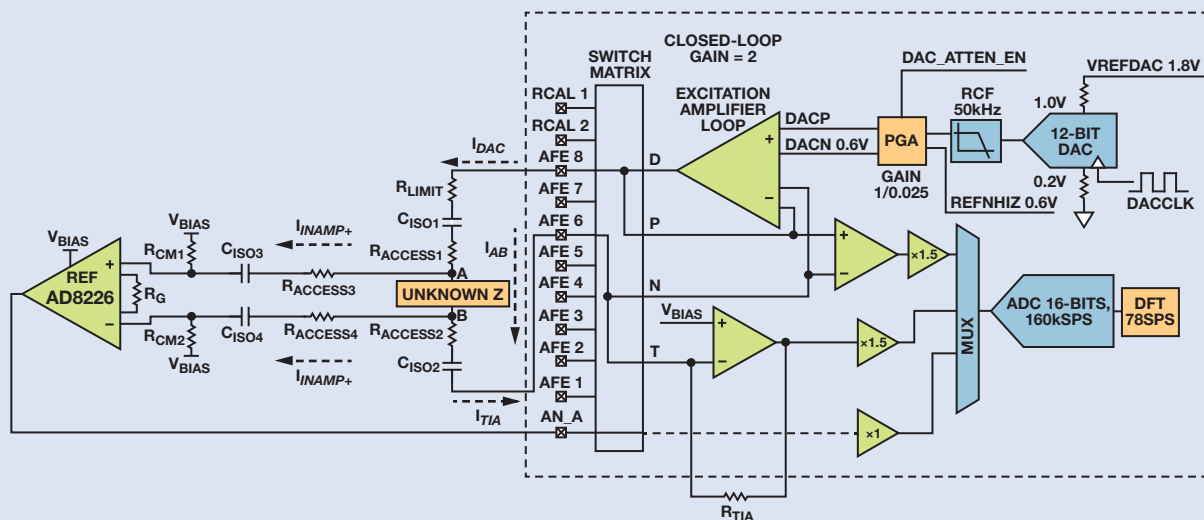


Figure 2. Four-wire isolated measurement circuit using ADuCM350 and AD8226.

Capacitors C_{ISO3} and C_{ISO4} block the dc level from the ADC, solving the half-cell potential problem and maintaining maximum dynamic range at all times. C_{ISO1} , C_{ISO2} , C_{ISO3} , and C_{ISO4} isolate the user, ensuring zero dc current in normal mode and in the first case of failure, and zero ac current in the first case of failure. Finally, resistor R_{LIMIT} is designed to guarantee that the ac current in normal operation is below the limit. R_{ACCESS} symbolizes the skin-electrode contact.

The ADuCM350 measures the current from the transimpedance amplifier (TIA) and the output voltage of the AD8226 to calculate the unknown body impedance. R_{CM1} and R_{CM2} must be as high as possible to ensure that most of the current flows through the unknown impedance and the TIA. The recommended value is 10 M Ω .

Design Limitations

This design presents some limitations when the electrode-skin impedance is close to 10 M Ω at the excitation frequency. The electrode-skin impedance must be significantly smaller than R_{CM1} and R_{CM2} (10 M Ω), or V_{INAMP+} will not be equal to A and V_{INAMP-} will not be equal to B , and the measurement accuracy will be degraded. The electrode-skin impedance is typically much smaller than 1 M Ω when the excitation frequency is greater than 1 kHz, as shown in Table 2.

Validation

To prove the accuracy of this design, the system was tested with different unknown impedances, with the results compared to those measured by an Agilent 4294A impedance analyzer. The magnitude error was less than $\pm 1\%$ in all the tests. The absolute phase error was less than 1° at 500 Hz and 5 kHz. The 9° phase offset error at 50 kHz could be corrected in software.

Conclusion

Designs for battery-powered, body-worn devices that measure bioimpedance must consider low power, high SNR, electrode polarization, and IEC 60601 safety requirements. A solution using the ADuCM350 and AD8226 was described here. Additional details, including complete design equations, can be found at www.analog.com/library/analogdialogue/archives/48-12/bio_imp.pdf.

References

Neuman, Michael R. "Biopotential Electrodes." *The Biomedical Engineering Handbook*, Fourth Edition. CRC Press, 2015
Chi, Mike Yu, Tzyy-Ping Jung, and Gert Cauwenberghs. "Dry-Contact and Noncontact Biopotential Electrodes: Methodological Review." *IEEE Reviews in Biomedical Engineering*, Volume 3, 2010.
http://en.wikipedia.org/wiki/IEC_60601



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