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A low power bioimpedance module for wearable systems☆

Stefano Rossi[a,b,*], Marco Pessione[a], Valeria Radicioni[a], Giovanni Baglione[a], Monica Vatteroni[b], Paolo Dario[b], Luigi Della Torre[a]

[a] Advanced System Technology (AST), STMicroelectronics, Via Olivetti 2, 20864 Agrate Brianza, Italy
[b] The Biorobotics Institute, Scuola Superiore Sant'Anna, Viale R. Piaggio 34, 56026 Pontedera, Italy

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ABSTRACT

In the emerging field of wearable systems for remote monitoring of physiological parameters, the measurement of bioimpedance has the potential to provide many useful information. On the other hand, in this scenario, an optimization of power consumption of the circuit is crucial. A low power architecture for the measurement of bioimpedance was identified in this work. It reduces the consumption in the most critical blocks of the system: the current driver, the signal sensing and the demodulator. The device was prototyped and electrically characterized. The compromise between power consumption reduction and the increase in electrical noise was analysed and an effective signal processing technique was developed, showing that it is possible to achieve a signal to noise ratio good enough to enable applications like respiration monitoring (breathing rate and amplitude) or cardiac output estimation. Preliminary tests on healthy subjects showed a good correlation with spirometer, for breathing monitoring, and with Doppler echocardiography, for cardiac output. Thanks to the good functionality and the reduced current consumption (750 μA at 2.8 V power supply was obtained with a discrete-components implementation) the module resulted suitable for the integration in wearable devices for remote monitoring of physiological parameters, or other low power applications.

1. Introduction

The term bioimpedance is commonly used to refer to the impedance of the human body or a part of it. The measurement of this parameter was employed in multiple fields, ranging from the assessment of body composition [1] or of intra-thoracic fluid status [2,3], to respiration, cardiac output and peripheral blood flow [4] monitoring.

Even if this technique is still not completely established in clinical practice, its versatility, simplicity and low cost make it very interesting also for the integration into wearable systems for remote monitoring of physiological parameters [5]. In this innovative and emerging scenario bioimpedance has been suited, for example, for respiration monitoring or for fluid status estimation, both in research projects [6] and commercially available devices [7].

On the other hand, in these particular applications, an optimization of the power consumption of the circuit is crucial.

Hardware for bioimpedance measurement is sometimes based on the impedance converter AD5933 (Analog Devices, Inc.) [8,9], which represents a simple solution. Anyway, it is not optimized in terms of current consumption (10 mA) and, furthermore, it requires additional external circuitry for bioimpedance measurement [10]. This causes an increase in power consumption, cost and complexity. A reduction of power consumption was obtained reducing the duty-cycle [11] of the measurements, or through application specific integrated circuit (ASIC) design [12]. The first approach is not compliant with scenarios requiring a continuous monitoring of the signal, e.g. breathing or cardiac output monitoring; the second guarantees very low consumption leveraging the advantages of full-custom design, but it is a very expensive solution.

The typically used architecture is shown in Fig. 1. The impedance is measured by injecting a fixed amplitude alternate current (typically sinusoidal) inside the body through an electrodes pair, and reading back the voltage drop from pickup electrodes. Being $I\cos(\omega t)$ the injected current, the read back voltage has the form:

$$v(t) = M_z(t) I \cos[\omega t + \phi_z(t)] \tag{1}$$

in which $M_z(t)$ and $\phi_z(t)$ are the module and phase of the bioimpedance, $Z(t)$. For this reason, after a first gain stage,

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* Corresponding author at: Advanced System Technology (AST), STMicroelectronics, Via Olivetti 2, 20864 Agrate Brianza, Italy. Tel.: +39 0396037249.

E-mail addresses: stefano.rossi@st.com (S. Rossi), marco.pessione@st.com (M. Pessione), valeria.radicioni@st.com (V. Radicioni), gio.baglione@gmail.com (G. Baglione), monica.vatteroni@sssup.it (M. Vatteroni), paolo.dario@sssup.it (P. Dario), luigi.dellatorre@st.com (L. Della Torre).

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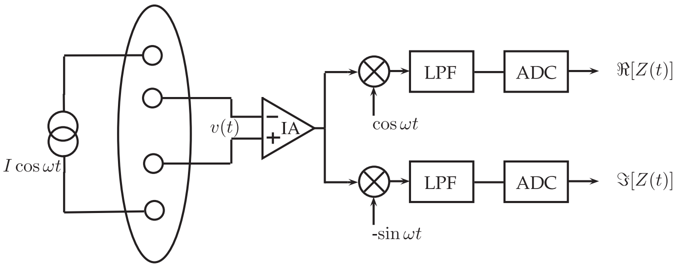

Fig. 1. Block diagram of a typical bioimpedance device using analog demodulators.

demodulation is needed to extract the information related to the impedance, in the form of real and imaginary part or module and phase components. Finally, analog or digital filtering can be used to divide the static and time dependent components of the impedance, typically referred as Z_0 and ΔZ.

A first critical element of this kind of architecture, in terms of power consumption, is the instrumentation amplifier (IA): since the typical working frequency for a bioimpedance system ranges from tens of kilo-hertz to mega-hertz, the bandwidth of the IA needs to be quite large. This usually means an increase in power consumption and also in cost, especially in discrete components design.

The same concept applies also to the current driver: to have small errors it is important to obtain a very high output impedance: the higher the output impedance, the lower the dependence of the current amplitude on the load. Since the load is constituted by electrodes to tissue impedance, it can vary a lot with frequency, electrode size and type, contact quality and so on. Unfortunately, the output impedance of common voltage to current converters (VI converters) is very high as long as the operational amplifier can be approximated as ideal, but quickly decreases with the increase in frequency, because of the limited gain-bandwidth product (GBP) of the operational amplifier. Therefore, a very high GBP is needed also for a 50 kHz working frequency [13], resulting in high current consumption. To relax the requirements for the current driver output impedance, current sensing is sometimes used (Fig. 2), but in this case two IAs are needed.

Demodulation is another critical block: it can be implemented with standard demodulators (as in Fig. 1), synchronous sampling [14] or gain and phase detection [15], but all these approaches require at least two channels, resulting in an increase in consumption, cost and size.

To solve all these issues, a novel hardware architecture to perform bioimpedance measurement is suggested in this work. The proposed changes are related to system architecture (Section 2) as well as to VI converter (Section 2.1) and demodulation (Section 2.2). The proposed bioimpedance module was prototyped and characterized. Breathing and cardiac output estimation were selected as applications to test the suitability of the impedance measurement system in real scenario; a proper processing scheme for the extraction of these parameters was designed and is presented in Section 3. Results of tests on healthy volunteers are presented in Section 4.

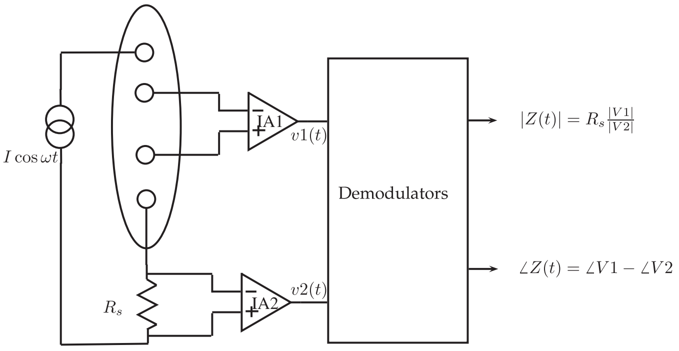

Fig. 2. Block diagram of a bioimpedance device using current sense resistor to measure the actual injected current.

2. Hardware overview

The block diagram of the proposed solution is shown in Fig. 3.

The driving current originates from a 50 kHz square wave, which is filtered with a second order low-pass filter to generate a quasi-sinusoidal voltage waveform. A VI converter is used to drive the current in the body. The demodulator is moved before the IA; therefore, the IA works on the baseband demodulated signal and the bandwidth requirements for this block can be dramatically reduced with important benefits in power consumption, cost and performance of the component. Nevertheless the VI converter and the demodulator, which are the blocks still operating at the working frequency, are optimized as described below (Sections 2.1 and 2.2) to reduce power requirements. Analog filtering is used to separate and amplify the AC coupled component ΔZ of the bioimpedance before the analog to digital conversion.

2.1. Current driver

The voltage to current converter is based on a modified Howland topology (Fig. 4), where we inserted a capacitor in the positive feedback loop.

The capacitor adds a pole to the output impedance expression; such a pole can be designed to give, together with the amplifier pole, a couple of complex and conjugate poles providing a peak at the corresponding frequency (Fig. 5).

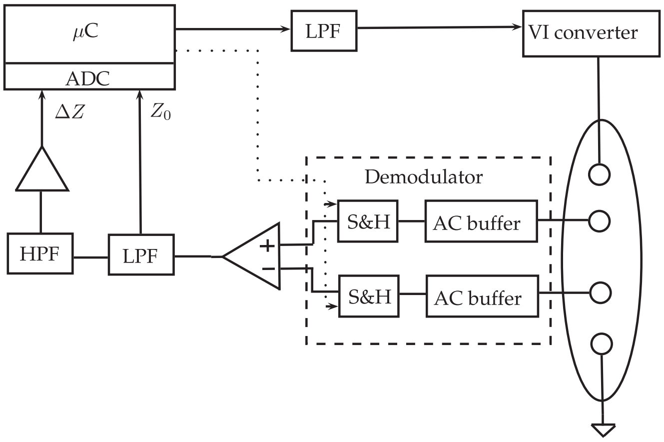

Fig. 3. Block diagram for the proposed bioimpedance device.

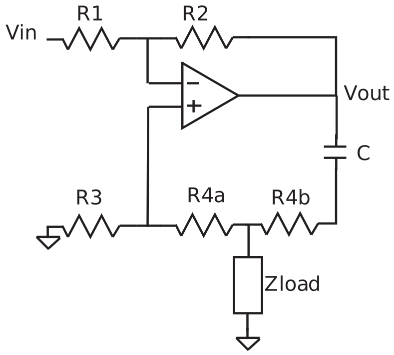

Fig. 4. Schematic of the VI converter.