

Current Source Design for Electrical Bioimpedance Spectroscopy

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INTRODUCTION

The passive electrical properties of biological tissue have been studied since the 1920s, and with time, the use of Electrical Bioimpedance (EBI) in medicine has successfully spread (Schwan, 1999). Since the electrical properties of tissue are frequency-dependent (Schwan, 1957), observations of the bioimpedance spectrum have created the discipline of Electrical Impedance Spectroscopy (EIS), a discipline that has experienced a development closely related to the progress of electronic instrumentation and the dissemination of EBI technology through medicine.

Historically, the main developments in EIS related to electronic instrumentation have been two: first, the progressive shift from “real studies,” where only resistance is measured, to “complex studies,” where the reactance is also measured. Second, the increasing upper limit of the measurement frequency makes it possible to perform studies in the whole β -dispersion range (Schwan, 1957).

Basically, an EBI measurement system obtains the relationship between voltage and current in an object, obtaining the impedance or the admittance according to Equations 1 and 2. In EBI, most of the systems measure the impedance of the tissue, therefore injecting a known current and measuring the corresponding voltage drop in the biological sample. See Figure 1(A).

$$Z = \frac{V}{I} \quad (1)$$

$$Y = \frac{I}{V} \quad (2)$$

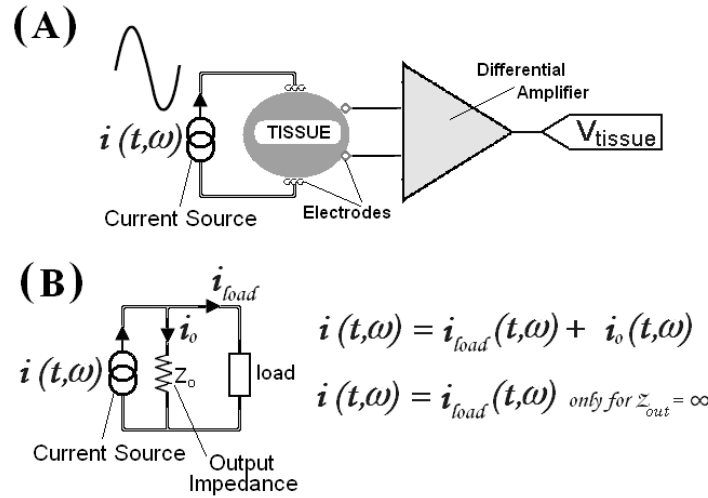
In an EBI measurement system, the current source plays a very important role, and its features are critical for the overall performance of the measurement system—especially for the frequency range of operation and the load dynamic range that the system is able to measure. The use of current driving instead of voltage driving is the most extended approach (Morucci & Rigaud, 1996), which applies an intrinsically safe current-limiting mechanism and reduces the possible nonlinearities. Given that the signal generator usually provides a voltage at its output, the current driver often is a Voltage Controlled Current Source (VCCS).

BACKGROUND

The functional purpose of a current source is to generate an electric current signal with a specific magnitude. Therefore, the output current is the most important characteristic of a current source, and parameters related to the output current define the performance of the source.

An ideal current source will provide exactly the same current to any load independently of its value at any frequency. To fulfil this aim, the output impedance Z_{out} must be very large, ideally ∞ , at all frequencies. See Figure 1(B).

Figure 1. (A) An ideal representation of a four-terminal voltage over current EBI measurement system; (B) representation of an ideal current source



In practice, the frequency range is limited to an operational frequency range at which the value of the output impedance of the source is very large in comparison with the value of the load. In bioimpedance applications, a commonly accepted value is at least 100 k Ω .

As a safety measure in biomedical applications, when current is injected into the body, the accumulation of electrical charges is avoided as much as possible. Therefore, the DC component of the stimulating current should be zero.

Over the years, there have been two main approaches in current source design: voltage-based structures and current-based structures. In voltage-based structures, what is responsible for the generation of the output current is the voltage in one or more nodes of the active circuit (e.g., the virtual ground in the case of Op-Amps). In a current-based structure, the output current is generated by an active device with intrinsic current-mode operation (e.g., Transconductance Amplifiers and Current Conveyors).

Voltage-Based Structures

Howland-based circuits and Load-in-the-Loop structures are the most common approaches to implement VCCS, and both are based on a single Op-Amp circuit. Another family of VCCS is based on a differential amplifier with unity gain and positive feedback.

Load-in-the-Loop

This current source design is one of the approaches first used to implement current sources with floating load (Sheingold, 1966). In Figure 2(A) it is possible to observe the principle of operation for the output current generation and the importance of the Op-Amp circuit. Note that as long as the Op-Amp provides a virtual ground and infinite input impedance, the output current is independent of the value of the load (i.e., the output impedance is infinite). Since the characteristics of an Op-Amp circuit are frequency-dependent, the output impedance of the current source exhibits a similar dependence. Equation 3 shows the analytical expression for the output impedance, Z_{out} , of the current source circuit in Figure 2(A), considering the frequency dependence of the differential gain (Seoane et al., 2007). Z_o and Z_{in} are the output and input Op-Amp impedances, and Z_i is the impedance which determines the transconductance of the VCCS, Z_i in Figure 2(A).

$$Z_{out} = \left(Z_o + \left(Z_{in} \parallel Z_i \right) (A_d(s) + 1) \left(1 - \frac{1}{2CMRR(s)} \right) \right) \quad (3)$$

Howland Source

This circuit topology (Sheingold, 1964) is probably the structure most used as a current source in EBI. Figure

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