# AN CURRENT SOURCE USING A NEGATIVE IMPEDANCE CONVERTER (NIC) FOR ELECTRICAL IMPEDANCE TOMOGRAPHY (EIT)

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***Abstract.*** *The purpose of this paper is to improve the output impedance of a current source used for Electrical Impedance Tomography (EIT) by using a Negative Impedance Converter (NIC). A Monopolar Howland Current Source(MHCS) and NIC circuits were implemented and then the output impedance was measured by a Data Acquisition (DAC) board of 12 bits resolution. A resistive load was used for investigating the performance of the MHCS with and without the NIC circuit when driving a constant ampitude sinusoidal current at 125 kHz through a single cable, a coaxial cable, or a coaxial cable plus a 32-channel multiplexer. Output impedance higher than 10.0 MΩ was measured for the single cable configuration without using the NIC circuit. Output impedance decreased to 13.6 kΩ when the MHCS was multiplexed and connected to a coaxial cable of approximately 90 cm long. However, when the NIC circuit was connected to the MHCS circuit the output impedance increased to approximately 3.0 MΩ.. These results show that accurate measurements can be achieved in single-frequency EIT systems.*

***Keywords****. current source, negative impedance, EIT*

## 1. Introduction

The mechanical ventilation is a worldwide known technique for keeping the vital biosignals of patients under control, especially in an Intensive Care Unit (ICU). It is important in ICUs to monitor the lungs of patients under mechanical ventilation. The ventilation strategy to be adopted by the medical staff depends on the actual clinical condition of the patient. Furthermore, the maintenance of the structure of the lungs will also depend on this strategy, which, in turn, will affect the patient's prognosis.

The EIT technique has been considered as a potential medical tool for imaging the respiratory cycle of patients under mechanical ventilation and for showing particular regions of the lungs with abnormal ventilation. The EIT technique consists of injecting an alternating current with constant amplitude between a pair of electrodes placed on the tissue surface and measuring all the resulting potential differences developed on others pairs of electrodes of the configuration. These potentials can be used to estimate either resistivity or conductivity distribution of, for example, a cross-section of the thorax.

However, to estimate the resistivity distribution is difficult, unless an accurate current source, which injects constant current into tissue, and a differential amplifier, which measures the potential differences, are used. Most of the accuracy needed can be achieved by designing a current source with high output impedance, $Z_{out}$. In theory, the $Z_{out}$ of the current source should be thousands times greater than the load (the load is the combination of the skin/electrode-interface impedance with the biological one). However, parasite capacitance in the output of the current source decreases significantly the $Z_{out}$ of the current source. Part of the current is not injected into the tissue.

The objective of this paper is to optimize the $Z_{out}$ of a current source by using a NIC circuit. A Monopolar-Howland-Current-Source (MHCS) is implemented and the $Z_{out}$ is measured with and without the NIC circuit, assuming four different loads in the MHCS circuit.

### 1.1. EIT: basic concepts

The general approach in EIT is to apply an electrical stimulus (e.g. a known current) to the material under study, to measure the resulting voltage and then to estimate either the resistivity or conductivity distribution. Either the resistivity or conductivity distribution inside the biological material under study forms an image. The stimulus can be applied in many forms, as described in Macdonald (1987). This paper concerns with EIT using the single-frequency sinusoidal stimulus, in which a constant current is applied to the tissue and the resulting voltage is measured. Most EIT systems use as many electrodes as possible in order to obtain better image resolution. The general principle of a 16-channel EIT system for measuring the resulting voltages in order to obtain the images is shown in Fig. (1). It is only shown a voltage developed between one electrode and the ground but 15 more independent measurements should be made. It can be shown that 240 independent differential voltages between adjacent electrodes can be measured. This number is defined by the term $N(N\text{-}1)$, where $N$ is the number of electrodes.

A Voltage-Controlled-Current-Source (VCCS) circuit is used to convert the sine wave, which is generated by the Sine-Wave-Generator (SWG) circuit, into a constant current. The voltage circuit, $V$, measures the differential voltage between the electrodes. Some implementations use a multiplexer to measure the differential voltage from many different electrode combinations.

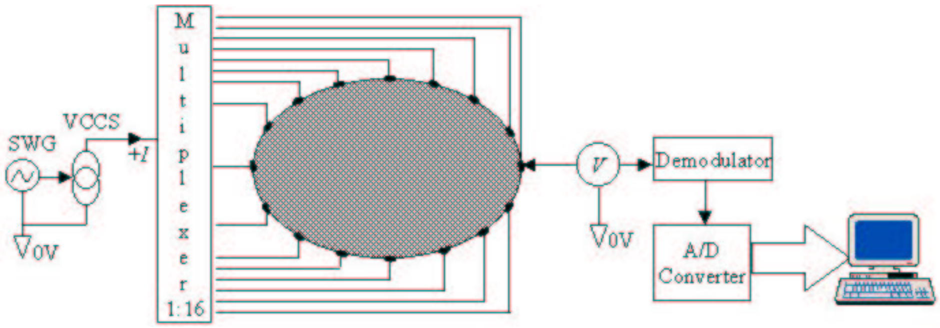


Figure 1. General concepts of a 16-channel EIT system for imaging a cross section of the human thorax, where $+I$ is the injecting current and $V$ is the measuring voltage.

It is a difficult task to measure the “true” impedance of a biological material (e.g. tissue). It is difficult to estimate the electrode/skin interface impedance and to maximise the instrumentation impedance over a wide frequency range (Denyer, 1993, Li, 1994, Lu, 1994, Bragós, 1994, Casas, 1996 and Bertemes-Filho, 2000). This is due to presence of parasitic capacitance to ground, which reduces the accuracy of the current injection and the voltage measurement circuitry. In theory, the current source and voltage measurement circuits should have high output and input impedance, respectively. However, cable capacitance, multiplexer *on*/*off* capacitance and other stray capacitance offered by the instrumentation reduce dramatically the $Z_{out}$ of the VCCS circuit, reducing the image accuracy. One way to reduce this error is to use NIC at the output stage of the VCCS circuit (Cook, 1994).

### 1.2. Improving the VCCS circuit

Most transfer impedance techniques use the VCCS circuit which converts a sine wave voltage $V_S$ into a current $I_S$ whose magnitude is unaffected by load impedance $R_L$. Figure (2a) shows a simple model of a monopolar current source. In practice, stray capacitance decreases the magnitude of $Z_S$ at higher frequencies. Hence the load current $I_L$ decreases with increasing frequency. Among the methods for improving the $Z_{out}$ of the VCCS circuit, the NIC circuit appears to be the most indicated when high stray capacitance must be significantly reduced. This is achieved by producing an equivalent negative capacitance $C_{in}$ in parallel with the stray capacitance. Figure (2b) shows the equivalent diagram of the NIC circuit used in this paper for improving the VCCS circuit. This NIC circuit uses positive feedback through $C_f$ to compensate for the current flowing into the stray capacitance $C_{stray}$. As a result, the equivalent output capacitance $C_{total}$ ($=C_{in}+C_{stray}$) can be adjusted by varying the gain of this circuit through the negative feedback resistance $P$, as shown in Equation (1).

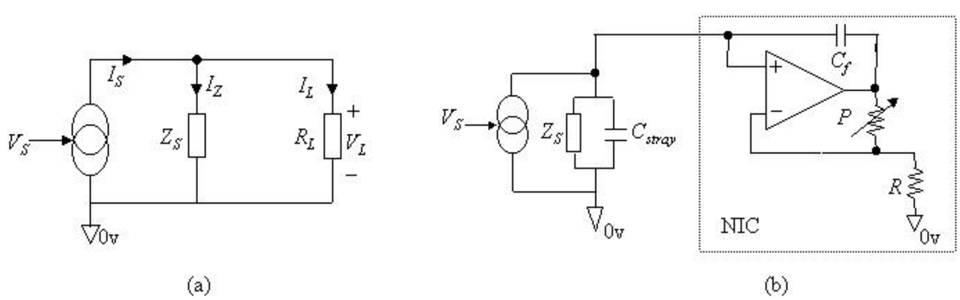


Figure 2. (a) Ideal model of a current source, where $I_S$ is the output current of the VCCS circuit controlled by $V_S$, $Z_S$ is the $Z_{out}$ of the VCCS circuit and $R_L$ is the load. (b) Diagram of the complete circuit used for improving the $Z_{out}$ of the VCCS circuit.

$$C_{total} = C_{stray} - \frac{P}{R} \cdot C_f \tag{1}$$

## 2. Methodology

A VCCS circuit based on the modified MHCS circuit and the NIC circuit were implemented. Figure (3) shows the complete implemented circuit for measuring the $Z_{out}$ with and without the NIC circuit. This type of VCCS circuit is fully described in Bertemes-Filho (2002).

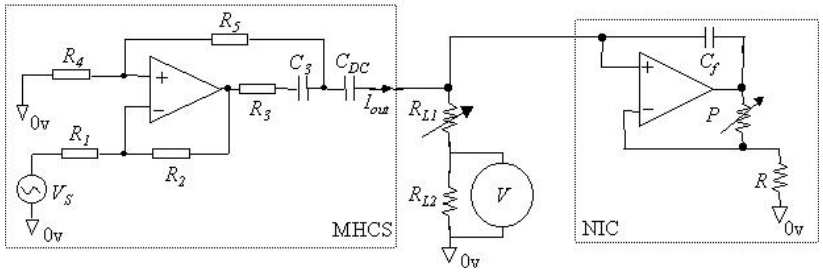


Figure 3. Schematic of the implemented MHCS and NIC circuits set to measure the $Z_{out}$, where $V$ is the voltage measurement system and $C_{DC}$ is the DC blocking capacitor.

When $R_1$=$R_2$=$R_5$=$R'$ and $R_4$=$R_3$+$R'$ then the output current $I_{out}$ can be defined by the ratio $V_S/Z_3$, where $Z_3$ is derived from the combination of resistor $R_3$ and the capacitor $C_3$. For the design of a constant current of 2 $m$A$_{p-p}$ at 125 kHz, $R_1$=$R_2$=$R_5$=$R'$=47 kΩ (±0.5%) and $R_3$=1 kΩ were used, assuming an input sine wave of 2 V$_{p-p}$. In order to obtain a high $Z_{out}$, the resistor $R_4$ must be equal to $R_3$+$R'$+Δ$R'$ (Bertemes-Filho 2002), where Δ$R'$ is the resistive increment for optimizing the $Z_{out}$ of the MHCS circuit. The NIC circuit is a non-inverting amplifier with gain 1+$P/R$, which has a capacitor $C_f$ of 330 $p$F in the positive feedback loop, $P$=10 kΩ and $R$=1 kΩ (±1%).

The $Z_{out}$ was measured by changing the load from 200 to 1,200 Ω. This method was initially proposed by Webster (1990) and it has been used by others (Bragós, 1994 and Bertemes-Filho, 2000). The method consists of measuring the difference of the current flow, $I_{out1}$-$I_{out2}$, across the resistor $R_{L2}$ when changing the total load ($R_{L1}$+$R_{L2}$) from 200 ($R_{L1}$=0) to 1,200 Ω ($R_{L1}$= 1 kΩ). The $Z_{out}$ can then be calculated according to Equation (2).

$$Z_{o} \approx \frac{I_{o1}}{\left|I_{o2}-I_{o1}\right|}\cdot \Delta R_L \tag{2}$$

where $I_{out1}$ (=$V/R_{L2}$) when $R_{L1}$=0 whereas $I_{out2}$ (=$V/R_{L2}$) when $R_{L1}$=1 kΩ and Δ$R_L$ (=$R_{L1}$) is the total load variation.

The voltage across $R_{L2}$ was measured by a Data Acquisition (DAC) board manufactured by Keithley Instruments, Inc. (KPCI 3110). A demodulation routine was developed in LabVIEW-6i in order to obtain the amplitude value of the voltage $V$ across $R_{L2}$. The data were acquired at a rate of 1250 ksamples/s, demodulated by using 1000 samples per cycle of sine wave, and then the $Z_{out}$ was calculated. The $Z_{out}$ data were recorded over a 6 minutes period.

The $Z_{out}$ was measured under four different conditions, such as: 1) $I_{out}$ was driven into the resistive load ($R_{L1}$+$R_{L2}$) through a single cable without the NIC circuit; 2) $I_{out}$ was driven into a capacitive load ($R_{L1}$+$R_{L2}$ in parallel with a capacitor of 151 $p$F) through a single cable with and without the NIC circuit; 3) $I_{out}$ was driven into the resistive load ($R_{L1}$+$R_{L2}$) through a coaxial cable (cable length of approximately 90 cm) with and without the NIC circuit (the cable screen was connected to the ground); 4) $I_{out}$ was driven into the resistive load ($R_{L1}$+$R_{L2}$) through a 32-channel multiplexer and coaxial cable with and without the NIC circuit.

The objective of using a capacitor in parallel to the resistor ($R_{L1}$+$R_{L2}$) in the experiments was to investigate whether the NIC circuit could compensate it. The capacitive load would decrease dramatically the $Z_{out}$, a significant part of the current $I_{out}$ would flow through the capacitor rather than the resistor. Therefore, it is expected an increase in $Z_{out}$ when the gain of the NIC circuit is correctly adjusted.

## 3. Results

Figure (4) shows $Z_{out}$ versus time for both resistive and capacitive loads with and without the NIC circuit. It can be seen that the $Z_{out}$ of the MHCS circuit is greater than 10.0 MΩ at 125 kHz for a resistive load but falling to approximately 78.6 kΩ when connecting a capacitor of 151 $p$F at the output of the MHCS circuit. It can also be seen that there is a very good improvement in the $Z_{out}$ (>10.0 MΩ) of the MHCS circuit when connecting the NIC circuit. It can be observed that $Z_{out}$ varied between 10.0 and 100.0 MΩ, which may be caused by the presence of noise and drift in the circuitry. Hence it was not possible to measure accurately values greater than 10.0 MΩ.

In order to reduce the level of noise in the measurements, a coaxial cable was used for connecting the MHCS circuit to the resistive load. Figure (5) shows the $Z_{out}$ of the MHCS circuit when the current is driven through a coaxial cable and through a "32-channel multiplexer+coaxial cable". The measured $Z_{out}$ without the NIC circuit is approximately

138.4 kΩ in the first situation whereas 13.6 kΩ in the second one. However, the $Z_{out}$ is greater than 3.0 MΩ in both situations when the NIC circuit is connected in the output of the MHCS circuit.

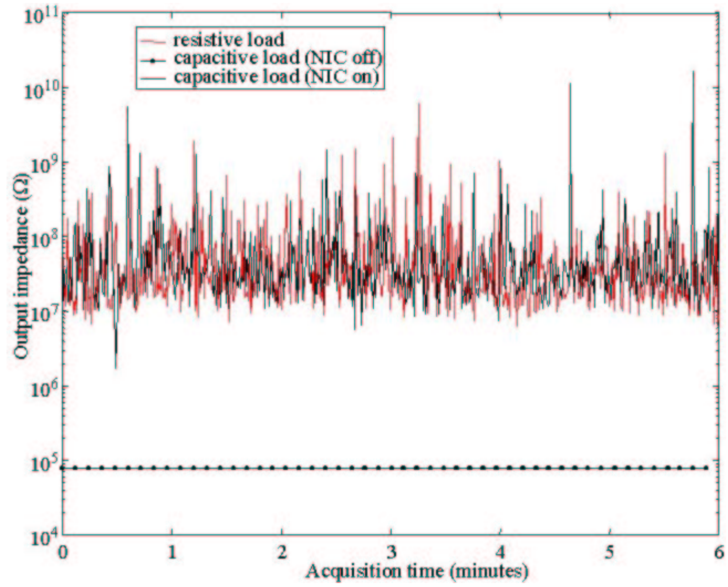


Figure (4). Measured $Z_{out}$ of the MHCS circuit versus time, using resistive load ($R_{L1}+R_{L2}$) and capacitive load ($R_{L1}+R_{L2}$)//151 pF (the symbol "//" denotes a parallel combination).

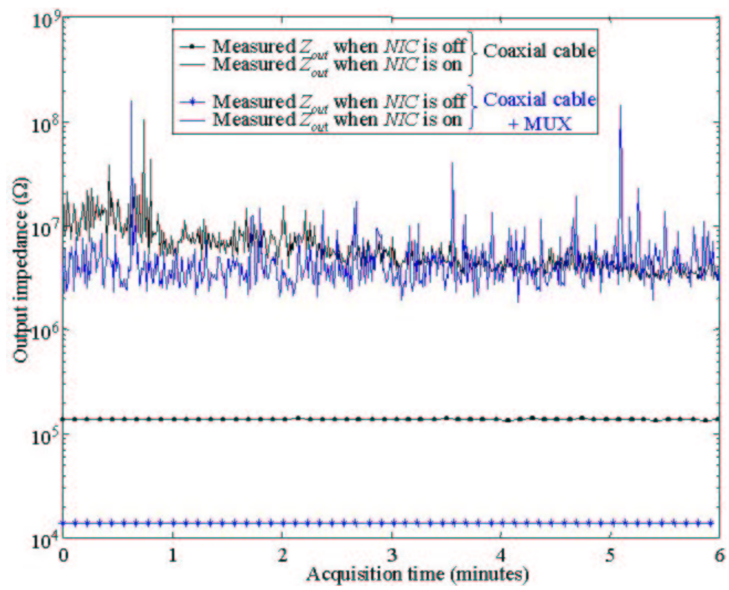


Figure (5). Comparison between the $Z_{out}$ of the MHCS circuit with and without the NIC circuit, using resistive load of (200+1000) Ohms driven through coaxial cable and multiplexer.

**4. Discussion and conclusions**

A VCCS circuit based on the MHCS with NIC circuit for improving the $Z_{out}$ was presented. Both MHCS and NIC circuits were stable at 125 kHz.

It was shown that the MHCS is very sensitive to capacitive loads. This was noticed when a capacitor of 151 *p*F was connected to its output. The $Z_{out}$ decreased from approximately 10.0 MΩ to 78.6 kΩ, when the NIC circuit was connected to the MHCS circuit the $Z_{out}$ increased to 10.0 MΩ. It was observed in the experiments a noise level of approximately 70 $\mu V_{rms}$ in the voltage measurements, degrading the accuracy of the $Z_{out}$ measurements.

The noise was reduced by using filters in the power-supply lines and coaxial cable. It was shown that the use of coaxial cable and the 32-channel multiplexer decrease dramatically the $Z_{out}$ of the MCHS circuit. The $Z_{out}$ of approximately 13.6 kΩ was measured when loading the MHCS circuit through the multiplexer and the coaxial cable whereas 138.4 kΩ when loading only with the coaxial cable. This may be explained by the presence of cable capacitance (e.g. approximately 90 *p*F) and multiplexer capacitance (e.g. approximately 417 *p*F) which degrade the $Z_{out}$ of the MHCS circuit. The greater the stray capacitance the higher the $Z_{out}$ degradation. Nevertheless, this capacitance was compensated and the $Z_{out}$ was increased to approximately 3.0 MΩ when the NIC circuit was used.

A VCCS with high $Z_{out}$ (i.e. 10,000 times greater than the load) was designed for a single-frequency EIT system using the NIC circuit. This may increase image resolution and accuracy from EIT systems.


## 5. Acknowledgement

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