A Novel Method to Determine the Bio-Impedance

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Abstract: In this paper, we designed a circuit to determine the amplitude and phase of biological impedances. The circuit is simulated by the Proteus software and the amplitude and phase values are compared with the theoretical values. The theoretical value is calculated according to the Fricke model and Cole-Cole model at a frequency ranging from 10KHz to 1MHz. The results of theoretical calculation are used to evaluate the accuracy of the designed circuit. The maximum error between simulation value and theoretical value is about 1.5% with Fricke model and about 1% with Cole-Cole model.

Keywords: Bioimpedance, measurement, simulation, Fricke model

1. Introduction

The electrical properties of biological tissues have been researched for many years and there have been many articles as well as practical applications [1][2][3]. Impedance is a useful parameter to determine the properties of biological tissue because they are conductive. Based on this parameter, many investigations are conducted such as the detection of frozen meat [4], detection of fat rate [5][6], the PH evaluation [7], tenders evaluation [8] or meat aging evaluation [9][10][11].

There are many studies on amplitude and phase of biological tissue impedance. The design of a specific integrated circuit for the measurement of tissue impedances has been presented [12] [13][14]. An impedance system was built to differentiate fresh chicken breasts from those that had been frozen and thawed [4]. A technique for real-time monitoring of bio-impedances using a Voltage Oscillation (VO) methodology was proposed [15]. The amplitude and phase-frequency characteristics in the extended band up to 5MHz was determined for the diagnosis of functional state and structure of biological objects with weakly expressed irregularities [16].

In fact, the state and structure of biological objects are changed by time and the kind of tissues. Thus, the electrical properties of biological tissues will be changed. The measurements of electrical properties will give information about the electrochemical processes in tissues and can be used to characterize the tissue or monitor for physiological changes. It is clear that acquiring these parameters requires the use of an expensive impedance analyzer and post processing of the data.

The purpose of this work is to present a novel system for determining the amplitude and phase of the biological tissue impedance. The information of amplitude and phase of bioimpedance have been used to extract relevant information from a biological material for the purpose of getting some details.

The paper is organized as follow. Section II describes the materials and methods to measure the biological impedance. Simulation results and evaluation of the accuracy of the design system are discussed in section III. Section IV concludes the paper.

2. Materials and Methods

2.1 Biological impedance models according to Fricke and Cole-Cole

To investigate impedance of biological tissue, it is necessary to view it according to an electrical model. The Fricke and Cole models are founded on the basis of the description given in Fricke [1][2] or Cole and Cole [17][18]. The impedance $Z$ is a complex function of alternating current frequency $f$:

$$ Z = Z_{\text{real}} + iZ_{\text{imag}} $$

Where $Z_{\text{real}}$ is the real part and $Z_{\text{imag}}$ is the imaginary part of the impedance $Z$.

One of the first successful electrical models was proposed by Fricke [1][2], which has been used extensively in research into cells or micro-organisms in suspension in a liquid medium [9]. Fricke considered biological tissue as ionized liquid medium (i.e., extracellular fluid (ECF)) suspending cells, which was intracellular fluid (ICF) enclosed by insulating membranes. Also, components of biological tissue (cell membranes, ICF, ECF) were represented by passive electrical elements [9]. The equivalent circuit represented tissue is shown in Figure 1. In which, $R_c$, $R_e$, $C_m$ respectively are resistance of ECF, ICF and capacitance of membrane.

![Figure 1: Electrical Fricke model with equivalent resistances](image)

The other successful electrical models was proposed by Cole-Cole impedance model [3][17][18] which also has been widely used for characterizing the electrochemical properties of biological tissues [19]. The equivalent circuit represented tissue is shown in Figure 2.
capacitance of the first amplifier, helping to maintain the loop by providing the charge required by the input amplifier equal to input voltage, $V_{in}$.

Forcing the voltage at non-inverting input level is forced across $R_1$ by amplifiers, the difference between the peak and the current amplitude and phase of the complex impedance $Z$.

From (1) and (2)

$$v(t) = V_z \sin(\omega t + \phi)$$

Where $\phi$ is the phase difference between the current and the voltage across the impedance $Z$. It is also the phase value need to find.

From (1) and (2), we have the formula for calculating the magnitude of the impedance $Z$:

$$Zx = \frac{V_z}{I}$$  \hspace{1cm} (3)

Transform equation (3), we have:

$$Zx = \frac{R_z V_z}{R_1 I} = \frac{R_z V_z}{V_r}$$  \hspace{1cm} (4)

The voltage across the complex impedance $Z,v(t)$, is taken by a differential amplifier. Two voltage amplitude values $V_z$ and $V_r$, determined by the wave peak detection circuit [20][21][22], asshown in Figure 4. This circuit uses two amplifiers, the difference between the peak and the current input level is forced across $R_1$. In the event of a rising pulse, the first amplifier compensates for the drop across diode $D_2$, forcing the voltage at non-inverting input of the second amplifier equal to input voltage, $V_{in}$. Diode $D_1$ is off and the voltage drop across resistor $R_1$ is zero. Capacitor $C_3$ speeds up the loop by providing the charge required by the input capacitance of the first amplifier, helping to maintain a minimal voltage drop across resistor $R_1$ in the sampling mode. A negative going edge results in diode $D_2$ turning off and diode $D_1$ turning on, closing the loop around the first amplifier and forcing $V_{out} = V_{in}$ across resistor $R_1$. The selection of capacitor $C_2$ and resistor $R_2$ is made by considering droop rate, settling time, and kickback. $R_2$ prevents overshoot from occurring at non-inverting input of the second amplifier. The time constants of $R_2$, $C_2$ are roughly equal to achieve the best performance. Slower time constants can be selected by increasing the value of capacitor $C_2$ to minimize droop rate and kickback at the cost of increased settling time. When the peak detector is required to hold the value of the peak for a long time, the capacitor should be buffered. An op-amp $U_2$, which should have high input impedance and low input bias current, is connected as a voltage follower.

Our purpose is to define the real and imaginary parts of the complex impedance $Z$, which can be presented in form of amplitude and phase.

The block diagram of system is shown in Figure 3. The value of $R$ is known and $V_s$ is taken from the AC source.

We have the phase difference $\phi$ is also the phase difference between the voltage $v(t)$ and the voltage on the resistor $R$ is $v_r(t)$. Transfer the two voltage signals above into two square-pulse signals using the comparators as shown in figure 4. If we feed the input of an EXOR gate with these two signals, it will be obtained a digital signal, $V_\phi$, called voltage phase, which duty cycle, $\delta$, is directly proportional to the phase to be measured [23].

V$\phi$ signal is passed through a second-order low-pass filter, shown in Figure 6, the output voltage is the voltage average value is proportional to the value of the phase to be calculated [24][25]. This second-order low-pass filter circuit has two RC networks, R1–C1 and R2–C2 which give the filter its frequency response properties. The filter design is based around a non-inverting op-amp configuration and the filter’s gain is equal to 1. The values of the resistors and capacitors determine the cut-off frequency of the low pass filter.

The cut-off frequency of the filter is calculated by the formula:
\[ f_c = \frac{1}{2\pi\sqrt{R_1 R_2 C_1 C_2}} \]
Here, \( R_1 = R_2 = 10 \text{ (kΩ)}; C_1 = C_2 = 47 \text{ (μF)}. \)
We have cut-off frequency, \( f_c = 0.33 \text{ Hz}. \)

**Figure 6:** Second order low pass filter circuit
The formula for phase calculation is:
\[ \phi = \frac{\text{Vout}}{\text{Vdd}} \times \pi \text{ (rad)} \]
Where \( \text{Vout} \) is the average output voltage
\( \text{Vdd} \): Supply voltage of the XOR gate

3. **Experiment Results**

Circuits are designed and simulated on the Proteus software, shown in Figure 7. The circuit is used to investigate the complex impedance \( Z \) according to the Fricke model and Cole-Cole model.

With Fricke model in Figure 1, the values of components are chosen as \( R_e = 2000\Omega, R_i = 1000\Omega, C_m = 1\text{nF} \). The frequency \( f \) is changed from 10KHz to 1MHz and the amplitude of the AC power supply is 2 V.

The complex impedance \( Z \) has the theoretical value calculated by the formula:
\[ Z = \frac{Re \times (Ri + Zc)}{Re + Ri + Zc} \]
In which:
\[ Zc = \frac{1}{j.2\pi f. C_m} \]
Formula for error calculation:
\[ \text{Error} = \frac{|S - T|}{T} \times 100\% \]
In which:
\( S \): Simulation value
\( T \): Theoretical value

The results obtained from the simulation are compared with theoretical values, are shown in the Figure 8 and 9. Figure 8 shows the amplitude values and figure 9 shows the phase values of the Fricke model. The blue line shows the theoretical value and the red line shows the simulation value. The green line shows the error between the theoretical and simulation values.

From the results, we can see that the difference between simulation and theory can be negligible, with the errors between theoretical and simulation values are smaller than 1.5%.
Figure 8: Change the impedance amplitude by frequency with Fricke model

Figure 9: Change phase impedance by frequency with Fricke model

With Cole-Cole model in Figure 2, the values of components are chosen as $R_e = 2000\, \Omega$, $R_i = 1000\, \Omega$, $C_s = 1\, \text{nF}$.

Figure 10: Change the impedance amplitude by frequency with Cole-Cole model
in practice to evaluate the impedance of materials such as meats or fruits.

4. Conclusion

This paper presents a simple method for identifying two amplitude and phase components in complex Z impedance, which may be equivalent to biological tissue, with frequencies varying from 10KHz to 1MHz. The simulation results obtained are promising for application circuit impedance measurement into practice with high accuracy. The maximum error value is 1.5% with Fricke model and 1% with Cole-Cole model. In the future, this circuit can be used in practice to evaluate the impedance of materials such as meats or fruits.

References


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