Electrical Impedance and Its Application

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Abstract

Bio-fields and medical purposes the use of electrical impedance tomography (EIT) is similar to electrical resistance tomography (ERT). EIT is a non-intrusive medical imaging technique where the conductivity or permittivity of a body part is casual from the surface electrode magnitudes. The Electrical conductivity arises due to the presence of free ions and varies considerably between various biological tissues or non-identical practical and other alike organs or tissues.. The Electrical impedance process is a novel technique to detect of malignant tissues that forms due to cervical, prostate, skin and breast cancer. Electrochemical impedance spectroscopy (EIS) is used to study surfaces, batteries, fuel cells, corrosions, photovoltaic systems, and some life science applications like Studying antibody-antigen binding, Study of electron transfer mechanisms of horseradish peroxidase etc.

Keywords: Electrical impedance; Reactance; Nyquist plot; EIS.

1. Introduction

Electrical impedance is shortly called as impedance which is an extension of the concept of resistance to AC (Alternating Currents). Unlike electrical resistance, Impedance has both magnitude and phase. But electrical resistance has only magnitude. Impedance opposes to current that depend on the frequency of the circuit. Impedance has both resistance and reactance. Resistance means obstruction of the electric-current that generates heat and reactance measure the adverse alternate current. Generally, electrical impedance shows the combined effect of resistance (R), inductive (X_L) and capacitive reactance (X_C) in an AC circuit. It may occur in a complete circuit or a particular section. Usually, resistance (R) refers the friction against the motion of electrons. It is found to some extent in all conductors except superconductors, and mostly voltage in resistors. Voltage drops when the AC passes through a resistance. Hence it is in-phase with the current. Reactance (X) is always inactive beside the mobility of electrons. It is observed rarely in both electric and magnetic fields, when voltage or current is applied, but mostly in capacitors and inductors. But in direct current (DC), resistance and electrical impedance have the same meaning. Impedance differs from resistance when current flows in DC are one way. For example, the process of open and close of an electrical switch, as inputting binary languages in the computers. Admittance is the opposite of impedance that measures the allowance of current. In the pure inductive circuit the current lags 90° (electrical) with respect to the applied-voltage, whereas in a pure capacitive circuit, current conducts 90° (electrical). But in a pure resistive circuit there is no lag nor lead of the current with respect to the applied voltage.

The electrical impedance is generally signified by Z. Mathematically, the impedance value can be expressed (Fig. 1) as in eq. (1)

$\boldsymbol{Z = \sqrt{R^2 + X^2}}$ ……………………. (1)

$X = X_L - X_C$ ………………………………………….. (2)

Where R is a circuit resistance value and known as a real part of impedance and imaginary part of impedance X is a circuit reactance value. Consistently resistance has positive value, but reactance is either positive or negative. The positive value is for inductive reactance and capacitive reactance has negative value In a circuit, resistance controls heat by dissolving power, whereas reactance reserves energy as a magnetic or electric field.

The phase formed within current and applied_voltage

$\theta = tan^{-1}(\frac{R}{X})$, ……………………………………………..………………………….(3)

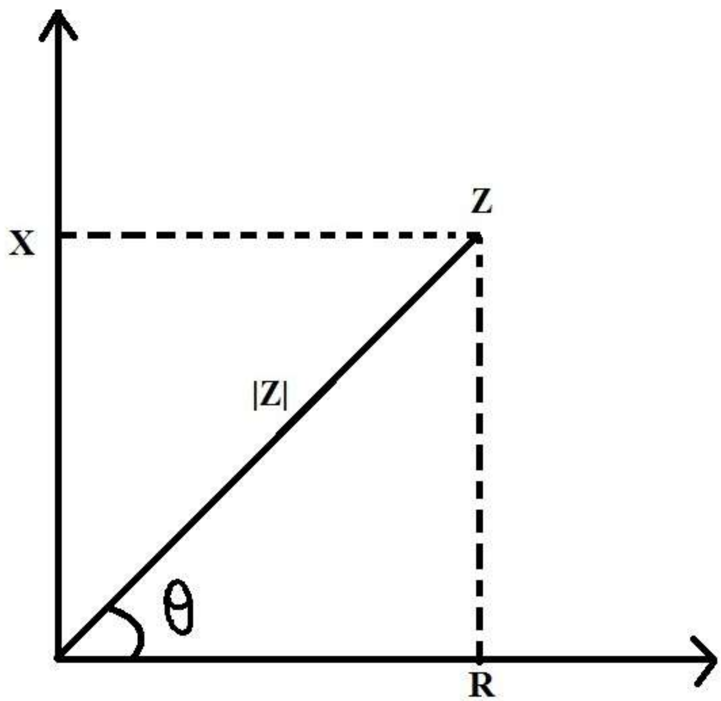

Fig.1 Resistance and Reactance circuit

The impedance of a 2- terminal circuit component is expressed as a complex part Z. The polar form has magnitude and phase behaviors altogather as eq. 4

$Z = |Z|e^{j\theta}$ …………………………………………………………… (4)

Where, $|Z|$ is the rate of the current amplitude against different range of voltage amplitude and ‘θ’ is the angle in between current and voltage. ‘j’ is the imaginary-unit.

1.1 Complex Impedance

A R value of resistor has R ohms of an impedance and it is a real number. The complex impedance (Z) of a standard inductor is $Z = j2\pi f_h L_h$**,** Where ‘f_h’ and ‘L_h’ are the frequency in Hertz and inductance in Henries respectively. The value of Z is imaginary as the standard inductors can only reserve and liberate electrical energy. It does not work as resistor due to lack of heat control. But the complex impedance of a standard capacitor is $Z = -j/2\pi f_h C_1$, Where ‘C_1’

is the capacitance (in farads). The real part of complex impedance is resistance and the imaginary part is reactance of the circuit. The impedance depends on the linkage of the capacitance (C) and resistance (R) like: R-C Circuit in Series, R-C Circuit in Parallel, Series R with R-C Circuit in Parallel. There are two types of graphs to evaluate the impedance result i.e. Argand or Nyquist_plots and Bode_plots. The Nyquist or complex-plane plot is the Z" (imaginary impedance) vs. Z' (real impedance) plot at different frequencies. Impedance is measured in Ohm and admittance is measured in ohm^{-1}.

1.1.1 R-C Circuit in Series

In this case the resistance and capacitance are connected in series (Fig. 2). The impedance is expressed by $Z(j\omega) = R - j/\omega C$…………………………………………… (5)

The admittance (Y) for this R-C connection is

$Y(j\omega) = \frac{1}{Z(j\omega)} = \frac{1}{R - j/\omega C}$ ………………………………………… (6)

Fig. 3 shows a Nyquist plot for a series connection is obtained as a vertical straight line 90^0 to the real axis. Another kind of graph is Bode-plots which is log |Z| (magnitude) versus log ω plot with phase angle ϕ. This series circuit is according to an ideal electrode (polarized) in solution, e.g., support of a mercury electrode to the electrolyte-solution. The admittance graph (Fig. 4) obtained for the series connection is a semicircular arc on the complex-plane graph. The imaginary impedance and admittance of the capacitive circuits has negative and positive value respectively.

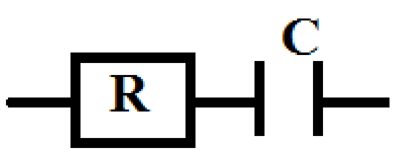

Fig. 2 Series R-C Circuit

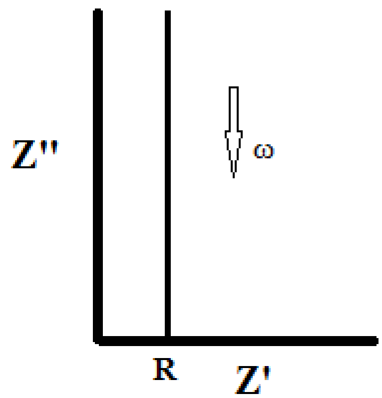

Fig. 3 Nyquist plot

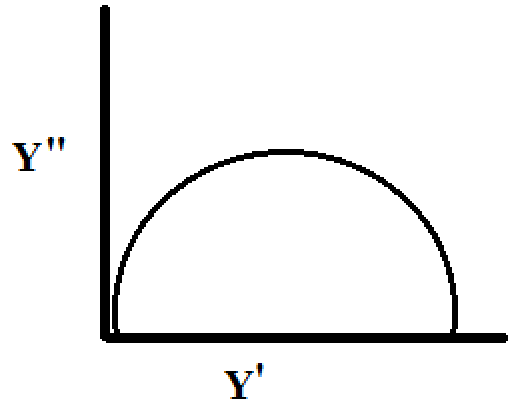

Fig. 4 Admittance plot

1.1.2 Parallel R-C Circuit

When an R-C connection is parallel (Fig. 5), the admittance is

$Y(j\omega) = 1/R + j\omega C$ ………………………………………………….(7a)

Hence, $Z(j\omega) = \frac{1}{\frac{1}{R} + j\omega C} = \frac{R}{1 + j\omega RC}$ ………………………………… (7b)

Here, the Nyquist plot (Fig. 6) represents a semicircular arc with having radius R/2 and the center is on the real-axis. the frequency near the maximum of the semicircle is $\omega = 1/RC$. The plot of complex-plane admittance shows a vertical line 90^0 to the real-axis [Fig. 7]. The admittance graph is resemble as the Nyquist plot for R-C connection in series.

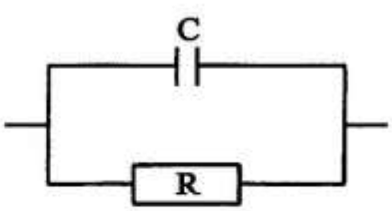

Fig. 5 Parallel R-C Circuit

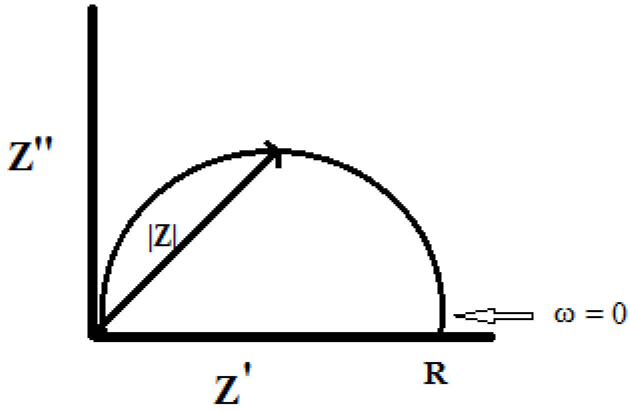

Fig. 6 Nyquist plot

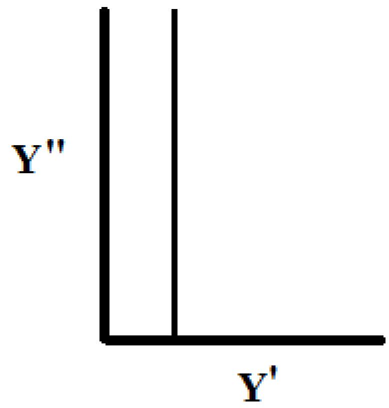

Fig. 7 Admittance plot

1.1.3 Series: Rs + Parallel R-C Circuit

Fig. 8 shows the circuit for Series: Rs + Parallel R-C. This connection consists the linkage of the resistance Rs in series with the parallel R-C circuit. The complex impedance is expressed as eq.8

$$Z(j\omega) = R_s + \frac{1}{\frac{1}{R} + j\omega C} \quad \textbf{(8)}$$

The corresponding Nyquist plot is shown in Fig. 9. The admittance complex plane plot is also shown in Fig. 10.

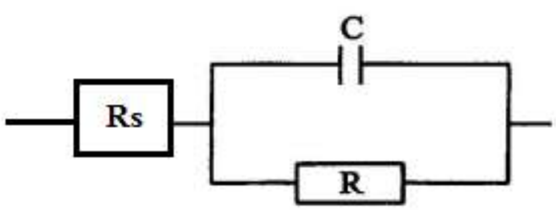

Fig. 8 Series: Rs + Parallel R-C Circuit

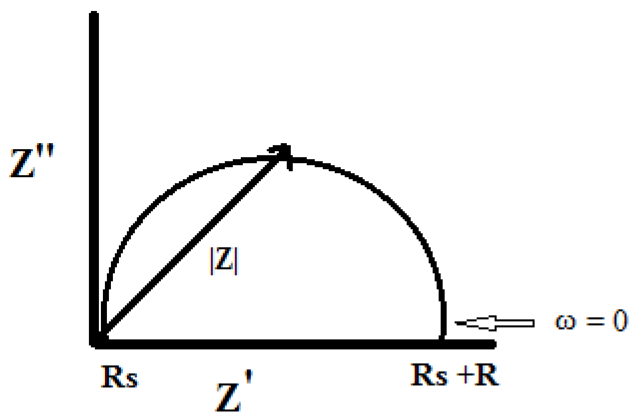

Fig. 9 Nyquist plot

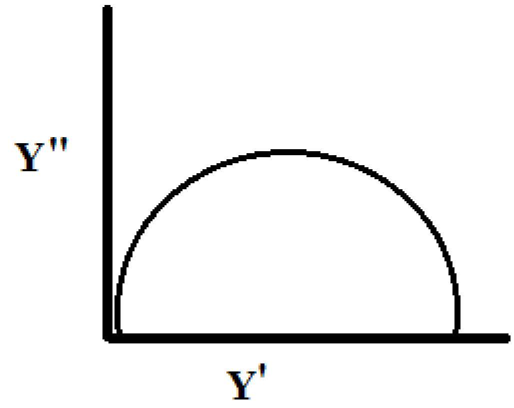

Fig. 10 Admittance plot

2. Study of Complex Impedance (Parallel circuit)

Complex impedance spectroscopy (CIS) plays an important role to characterize multiple electrical properties of the material as well as their interfaces with electrically conducting electrodes. The motion of mobile charges can be analyzed in the grain (bulk) or grain boundary (interfacial) zones of different solid or liquid materials. From this ionic, semiconducting, mixed electronic-ionic, and even insulators (dielectrics) properties of the materials can be investigated. An identical circuit supported impedance spectra gives the idea of the physical behaviors that present in the core of the material. The ideal ceramic has both bulk and interface zones with unique physical behaviors. These zones are well analyzed in the impedance spectra. The complex impedance Z* (ω) is normally given by the eq. 9.

$$\boldsymbol{Z^{*} = Z'(\omega) - jZ''(\omega)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Where $\boldsymbol{Z'(\omega) = \frac{R}{1+(\omega\tau)^2}}$ and $\boldsymbol{Z''(\omega) = \frac{\omega R\tau}{1+(\omega\tau)^2}}$ are the real_part and imaginary_part of the complex-impedance respectively. R is AC resistance and $\tau = RC$.

At low frequency zone Z′ value is more and slowly Z′ value reduces with a rise in frequency. But in a certain frequency the Z′ value increases with rise in temperature. These types of behaviors suggest the growth of AC conductivity mechanism towards high temperature and frequency. At higher frequency zone, the fusion of Z′ shows the liberation of space charges that controls AC conductivity. Since the declination of Z′ value at low frequency zone according to temperature indicates Negative Temperature Coefficient of Resistance behavior of the sample []. The peak point of Z″ is shifted towards high frequency zone with a rise in temperature. The peak width reveals the temperature dependent relaxation phenomenon []. The merging of Z″ (moreover Z′) at high frequency zone for each temperature provides the possiblity of liberate in space charge polarization (or accumulation) near the boundaries of uniform phases in the applied-external field. At low temperature region the monotonous decrease in Z′ value suggests the relaxation mechanism in the materials. This shows the temperature-dependancy relaxation process in the materials. The characteristics of impedance of a material are explained by the semicircular arc as shown in Fig. 6. The pattern of Nyquist plot is changed according to the temperature[]. The complex impedance spectroscopy (CIS) is an important spectra to determine, analyze, and interprete the dynamics of electrical conduction mechanism like: hopping rate, conductivity relaxation time. The deviation in Debye type relaxation is observed in the RC network, when a constant phase element (CPE) is introduced to the circuit. It gives an penetration into the electrical passages depicted by the lowest capacitance of the materials. In spite of the investigation and explanation of the experimental datas, a model equivalent circuit is necessary to get an actual presentation of the electrical behaviors [23]. The semicircular behavior of the Nyquist-plot explains the excellent model for both the grains and grain_boundaries in the individual resistive or capacitive behaviors of materials. Different types of circuit like; {(CQR)(CR)}(Fig. 11), {(CQR)}(Fig. 12) are suggested to measure R, C, and Q (the respective resistive and capacitive components). where C and Q are Jonscher's universal power components: $C=A(j\omega)^{p-1}$ and $Q=A(j\omega)^{n-1}$ [39]. Parameters of the above circuit {(CQR) (CR)} can be evaluated by using a Software package (ZSIMP WIN-2) []. In {(CQR) (CR)}, two parallel RC combinations (R_b, C_b, R_{gb}, C_{gb}) are connected in series. R_b, C_b are bulk resistance and capacitance respectively, whereas R_{gb}, C_{gb} are grain boundary resistance and capacitance respectively.

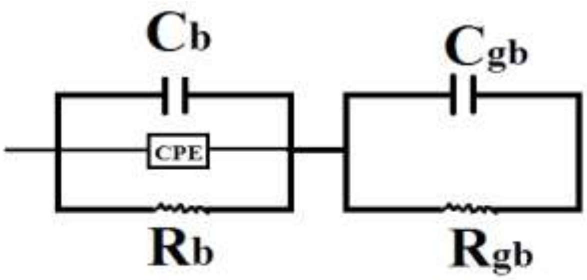

Fig. 11 {(CQR) (CR)} circuit model

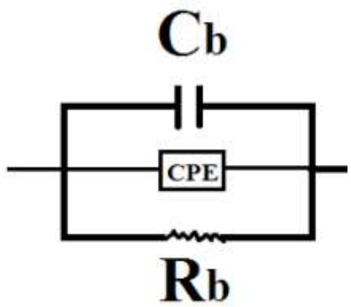

Fig. 12 {(CQR)} circuit model

3. Applications of Impedance

The importance of both impedance and resistance in electronics and magneto-electric appliances is more in daily life. These are very common in household appliances. The panel board present in buildings has fuses that control electricity and electric surge by interrupting the power system. That minimizes the injury. The fuses are akin to extreme capacity-resistors that has the capability to take the blow. It works as a circuit breaker or stabilizer which protects the device from damage. In capacitors, impedance is applied to control the electricity flow into a circuit board. Without the capacitor alternating currents will either fry or go berserk as the electricity in AC fluctuates more. The capacitor allows the electricity to go smoothly to manage overload / under-load.

Reference

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