

Simplify the resolve of AC parameters such as immittances, conductivity and dielectric by using the delay-time measurement

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Abstract

Our novelty for the presented work is to find a simple method to study electric and dielectric properties for samples such as magnetic materials. We focus on prepare and characterize of the ferrites. During the AC measurements, we struggled to use the Lissajous figure. In addition, we have a shortage of equipment for measurements. This prompted us to look for a method to be easy to use with simple devices. The Delay-Time measurement method for any two different sinusoidal waves was used to calculate the phase shift (φ) between them using an oscilloscope. The φ was exercised to resolve the series and the parallel of RC in AC circuit. The phasor diagram of the series and the parallel of RC in AC circuit were plotted. All the main and derived quantities of the AC circuit were calculated, such as the immittances, conductivity and dielectric parameters. The presented method is considered as a simple method comparing to other methods. Thus, it can be replaced the other methods as well as it can be used from the scientists and engineers. Our Master students already used this method and they got good results. This paper is considered to be a preliminary analysis for this simple method and we will develop it. Copyright © 2017 VBRI Press.

Keywords: Electrochemistry, phase difference, immittances, conductivity, dielectric, impedance.

Introduction

In the last decades, the emphasis in electrochemistry has shifted from a time/focused dependency to frequency-related phenomena, a trend toward alternating current (AC) small-signal studies [1]. The importance of AC small-signal studies is to measure different quantities such the immittances: impedance, admittance, modulus and dielectric permittivity, and conductivity for the materials. There are, several, studies of the effect of polycrystallinity on these quantities of solid dielectric materials [2-4]. Nevertheless, the problem was to measure the impedance of the solid dielectric materials. The electric and the dielectric properties of the materials that undergoes to AC can be determined and/or measured using number of methods. Based on somewhat oversimplified physics model, sample such as ferrite materials can be formed as a disc is considered as a capacitor in AC circuit. Thus, a capacitor is composed of two conductive plates separated by examined material. This forms the capacitor with double electrical layers (DELs). DELs and their inherent capacitive reactance are distinguished by their relaxation times, or more realistically by the distribution of their relaxation times [1]. The electrical response of the capacitor, which can deal as a heterogeneous cell, can vary substantially

depending on the species of charge present, the microstructure of the dielectric material, electrolyte, the texture and nature of the plates [1,4]. The capacitor has beside the most important property: the capacitance, also parasitic or stray properties. On the other hand, parasitic has effects on the circuit behavior: 1- An increase in propagation delay or equivalently, a drop in performance, 2. An impact on the energy dissipation and the power distribution and 3. An introduction of extra noise sources, which affects the reliability of the circuit [5]. The two parallel plates have a certain separation length and, therefore, they have a certain resistance and self-inductance that are connected in series or parallel with the actual capacitance. The model of a capacitor with its parasitic components is shown in the Fig. (1). The ohmic resistance and self-inductance depend strongly on the physical structure. In addition, the dielectric plays a major role and is represented as an ohmic resistance. The electrolyte in electrolytic capacitors also has an ohmic



Fig. 1. Geometric model of the capacitor in AC circuit.

resistance. This study focuses on the measurement method of the reactance and the equivalent resistance (ER). Therefore, it can be calculated different quantities. Regards to the other parasitic self-inductance another measurement methods must be used that may be described later on. However, the effects of the inductance are noticeable as spikes in the oscilloscope image.

Conception of impedance

Impedance (Z) may be defined not only for discrete systems but also for arbitrary distributed systems as the Fourier transform (FFT) of the differential equation defining the voltage response divided by the FFT of the periodic current excitation [1]. However, FFT only reduces differential equations to simple Ohm’s law-like form under conditions of linearity, causality, and stationarity of the system; therefore, Z is properly defined only for systems satisfying these conditions. Z has a more general conception than resistance (R) in the AC circuit because it considers phase differences. It becomes a fundamental and essential concept in different engineering disciplines. Thus, there are different methods to measure the Z. An impedance Z^* is considered as a complex vector quantity (Z^*), which can be functioned in the applied frequency as follows:

$$Z^*(\omega) = Z' + jZ'' \tag{1}$$

where Z' and Z'' are the real and imaginary parts of the Z^* , respectively. The three quantities Z^* , Z' and Z'' can be represented in the plane with either rectangular or polar coordinates as will explain later in this paper. In the simplest analysis the Z of the series and parallel RC circuits. In qualitatively considering the Z behavior of series or parallel RC circuits, it is always useful to reduce the limiting cases that arise for $\omega \rightarrow 0$ or $\omega \rightarrow \infty$. Then, respectively, $X_C \rightarrow \infty$ or $X_C \rightarrow 0$. The behavior for these cases is usually obvious, bearing in mind $Z'' = X_C = -j\omega C$ [1]. The methods I and II represent the electrical configurations encountered in measurement and interpretation of experimental Z spectroscopic behavior of the double-layer at electrode interfaces.

Phase difference measuring for sinusoidal waves

There are a number of ways to measure the phase difference or shift (φ) between more than one waveforms using an oscilloscope. These ways are Delay-Time, Lissajous, Product and Curve-fitting. The advantages and limitations of each were summarized in Table (1). It is noticed that, from Table (1) that the best method to calculate the φ is the Delay-Time, which is, also, considered to be easiest method comparing with the others. In straight forward, as shown in the Fig. (2) φ can be calculated by measuring the Delay-time (Δt) for two different sinusoidal waves as follows:

$$\varphi = \omega \Delta t \tag{2}$$

where $\omega = 2\pi f$ is the angular frequency for the two different sinusoidal waves and f is the frequency.

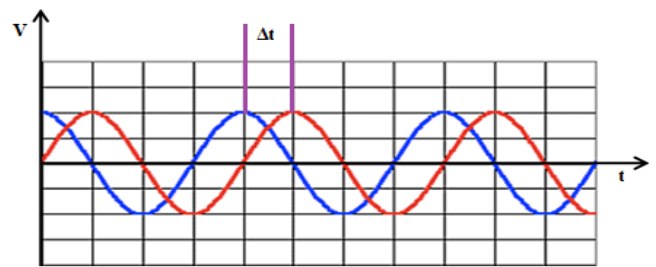


Fig. 2. Phase shift between two waveforms.

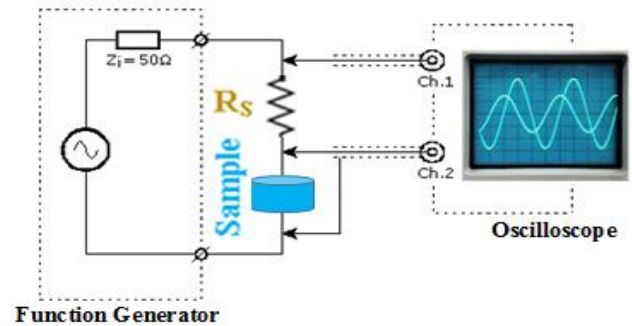


Fig. 3. Measurement arrangement for a capacitance measurement with a sine wave voltage.

Fig. (3) illustrates that, the sample is inserted in a half bridge configuration with the sinewave function generator. By measuring the Δt between two voltages waveforms and, consequently, calculating the φ between them, different physical quantities can be determined such as the reactance (X_C) and the equivalent resistance (ER). Herein, two methods I and II are detailed to calculate the X_C and the ER in the parallel and series connections

Method I: Parallel method

In this method, the sample can be presented as a capacitor connected with a parallel resistor (R_{EP}) as the circuit shown in Fig. (4), which consists of a known resistor (R_S) and the sample with unknown impedance (Z_{SP}). This circuit, can be used to calculate the capacitive reactance (X_{CP}) and R_{EP} , consequently, calculating the Z_{SP} and other parameters. Experimentally, the bridge voltage (V_T) and the voltage a cross the resistor (V_{RS}) can be measured by the oscilloscope using two channels as shown in Fig. (3). In addition, the Δt between V_T and V_{RS} as well.

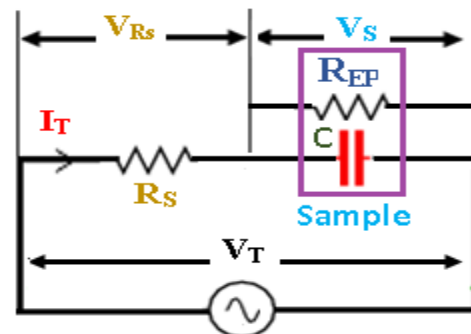


Fig. 4. The parallel model of the sample an AC circuit.

To resolve the presented circuit in **Fig. (4)**, it can be plotted the associated vectors (phasors) diagram as shown in **Figs. 5 (a and b)**. The currents phasor diagram is depicted in **Fig. (5a)**, where the voltages phasor is diagrammed in **Fig. (5b)**. Mathematically, after measuring V_T , V_{RS} and Δt it can be found different parameters such that the total currents (I_T), which is divided to two components in the sample; the current passing through capacitor (I_C) and the current passing through parallel resistor (I_{REP}) as shown in the **Fig. (5a)**. Moreover, the voltage across the sample (V_S) and the phase angles (δ and α) as illustrated in **Fig. (5b)**.

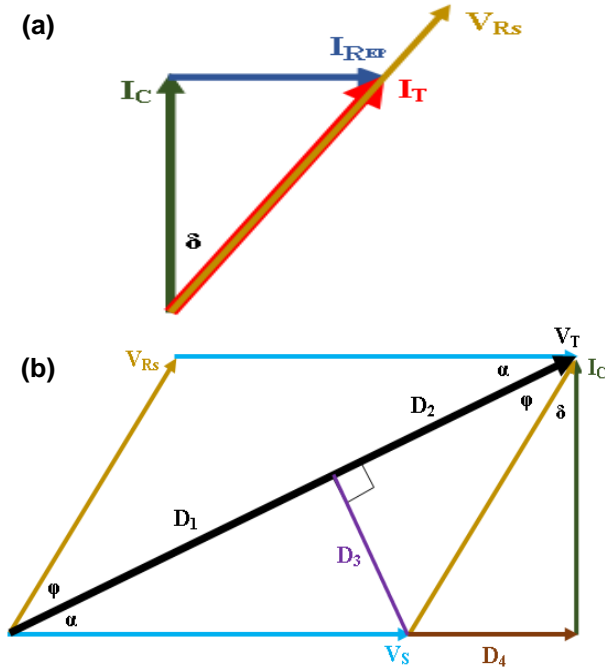


Fig. 5. Phasor diagram for AC circuit in **Fig. (4)**.

Based on the phasor diagram in **Fig. (5b)**, the phase shift (φ) between the two sinusoidal waves V_T and V_{RS} can be calculated by using Eq. (2).

The total current (I_T) passing through the circuit is calculated with the aid of known R_S by measuring V_{RS} .

$$I_T = \frac{V_{RS}}{R_S} = \frac{V_S}{Z_{SP}} = \frac{V_T}{Z_T} \quad (3)$$

Although, it can also, be determined by measuring the voltage across the sample (V_S) or the bridge voltage (V_T) as in Eq. (3). On the other hand, there is a problem to determine or measure the impedance of the sample (Z_S) as well as the total impedance (Z_T). Therefore, these parameters can be calculated by using the circuit in **Fig. (4)** and the phasor diagram in **Fig. (5)**.

Referring to **Fig. (5b)**, the V_S can be given by

$$V_S^2 = D_1^2 + D_3^2 = (V_T - D_2)^2 + D_3^2 \quad (4)$$

where $D_1 = V_S \cos \alpha$, $D_2 = V_{RS} \cos \varphi$ and $D_3 = V_{RS} \sin \varphi$. Now, substitute into Eq. (4) to get

$$V_S = [(V_T - V_{RS} \cos \varphi)^2 + (V_{RS} \sin \varphi)^2]^{1/2} \quad (5)$$

Since

$$D_3 = V_S \sin \alpha = V_{RS} \sin \varphi \quad (6)$$

Now, the phase angle (α) between the two voltage waves V_T and V_S can also be calculated by rearranging Eq. (6), as follows

$$\alpha = \sin^{-1} \left[\frac{(V_{RS} \sin \varphi)}{V_S} \right] \quad (7)$$

Depending on the **Fig. (5b)**, the sum of all phase angles ($\varphi + \alpha + \delta = 90^\circ$). By using Eq. (7), the phase angle (δ) can be expressed by

$$\delta = \left[90^\circ - \left(\varphi + \sin^{-1} \left[\frac{(V_{RS} \sin \varphi)}{V_S} \right] \right) \right] \quad (8)$$

Because the sample in the circuit is presented as a capacitor and a parallel resistor as in **Fig. (4)**, the V_S and the voltage across the capacitor (V_C) have the same value i.e. $V_S = V_C = I_C X_{CP}$. Using the **Fig. (5a)**, $I_C = I_T \cos \delta$, as a result the capacitive reactance (X_C) can be found by

$$X_{CP} = \frac{V_S}{I_T \cos \delta} \quad (9)$$

As a result, the capacitance can be given by

$$C_P = \frac{I_T \cos \delta}{\omega V_S} \quad (10)$$

Again, as in **Fig. (4)**, the V_S and the voltage across the parallel resistor (V_{REP}) have the same value i.e. $V_S = V_{REP} = I_{REP} R_{EP}$. Using the **Fig. (5a)**, $I_{EP} = I_T \sin \delta$, thus R_{EP} can be calculated from

$$R_{EP} = \frac{V_S}{I_T \sin \delta} \quad (11)$$

According to the **Fig. (5a)**, the magnitude of the impedance of the sample (Z_S) can be added reciprocally:

$$\frac{1}{Z_{SP}} = \frac{1}{R_{EP}} + j \frac{1}{X_{CP}} \quad (12)$$

Rearrange the Eq. (12), it becomes

$$\frac{1}{Z_{SP}} = \frac{X_{CP} + jR_{EP}}{R_{EP} X_{CP}} \quad (13)$$

In order to separate the real and imaginary components of impedance in this equation numerator and denominator are multiplied by the rationalizing complex conjugate of $X_{CP} + jR_{EP}$, viz $X_{CP} - jR_{EP}$, giving

$$\frac{1}{Z_{SP}} = \frac{(X_{CP} + jR_{EP})(X_{CP} - jR_{EP})}{R_{EP}(X_{CP} - jR_{EP})} \quad (14)$$

$$\frac{1}{Z_{SP}} = \frac{X_{CP}^2 + R_{EP}^2}{R_{EP} X_{CP} - jR_{EP}^2} \quad (15)$$

So that, Z_{SP} can be given by

$$Z_{SP} = \frac{R_{EP} X_{CP}}{X_{CP}^2 + R_{EP}^2} - \frac{jR_{EP}^2}{X_{CP}^2 + R_{EP}^2} \quad (16)$$

Based on the Eq. (1), the real Z' and the imaginary Z'' of Z_S are given by

$$Z' = \frac{R_{EP} X_{CP}}{X_{CP}^2 + R_{EP}^2} \text{ and } Z'' = \frac{jR_{EP}^2}{X_{CP}^2 + R_{EP}^2} \quad (17)$$

The magnitude or modulus of Z_{SP} ($\text{mod}|Z_{SP}|$) can be calculated from Eq. (16) as follows

$$\begin{aligned} |Z_{SP}| &= \sqrt{\left[\frac{R_{EP} X_{CP}}{X_{CP}^2 + R_{EP}^2} \right]^2 + \left[\frac{R_{EP}^2}{X_{CP}^2 + R_{EP}^2} \right]^2} \\ &= \sqrt{\frac{R_{EP}^2 (X_{CP}^2 + R_{EP}^2)}{(X_{CP}^2 + R_{EP}^2)^2}} = \sqrt{\frac{R_{EP}^2}{X_{CP}^2 + R_{EP}^2}} \\ &= R_{EP} (X_{CP}^2 + R_{EP}^2)^{-1/2} \end{aligned} \quad (18)$$

The equivalent electric conductivity of the sample in the parallel model (σ_{SP}) can be expressed as

$$\sigma_{SP} = \frac{T(X_{CP}^2 + R_{EP}^2)^{1/2}}{A R_{EP}} \quad (19)$$

where A and T are the area and separation thickness of electrode.

Moreover, the total impedance (Z_T) for the circuit show in Fig. 4 can be determined as

$$Z_T = [(R_S)^2 + 2R_S Z_{SP} \cos(90 - \delta) + (Z_{SP})^2]^{1/2} \quad (20)$$

But $\cos(90 - \delta) = \sin(\delta)$, so Eq. (20) becomes

$$Z_T = [(R_S)^2 + 2R_S Z_{SP} \sin(\delta) + (Z_{SP})^2]^{1/2} \quad (21)$$

In addition, one of the important dielectric parameter is the dielectric loss factor ($\tan \delta$), which is indicated of the power dissipation in the circuit. $\tan \delta$ can be concluded from Fig. (5) and Eqs. (9 and 11)

$$\tan \delta = \frac{I_{REP}}{I_C} = \frac{V_{REP} X_{CP}}{R_{EP} V_{CP}} = \frac{X_{CP}}{R_{EP}} \quad (22)$$

Method II: Series method

As represented in the Fig. (6), the circuit consists of sample and a series resistor (R_{ES}). This circuit, can be used to calculate the capacitive reactance (X_{CS}) and R_{ES} . This method describes a measurement that is suitable for measuring on larger capacities and can determine R_{ES} . This method is thus mainly suitable for measuring on electrolytic capacitors.

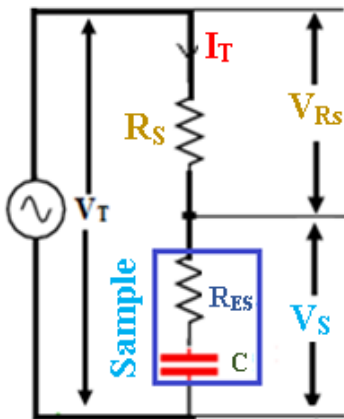


Fig. 6. The sample connected in an AC circuit of a half bridge configuration.

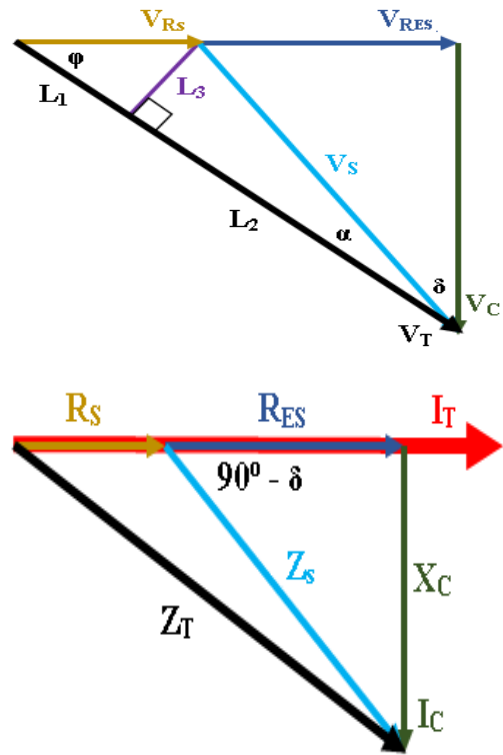


Fig. 7. Phasor diagram for AC circuit in Fig. (6).

To resolve the given circuit, it can be plotted the associated phasors diagram as shown in Fig. 7(a and b). The voltages phasor diagram is represented in Fig. (7a), where the currents phasor diagram is showed in Fig. (7b). Mathematically, after measuring V_T , V_{RS} and Δt , it can be found different parameters such that the total currents (I_T) and consequently, the voltage across the sample (V_S) and the phase angles (δ and α) as shown in Fig. (7a).

Depending on the phasor diagram in Fig. (7a), the ϕ between the two voltages waves V_T and V_{RS} can be determined by using Eq. (2). Herein, I_T is calculated with the aid of known R_S by measuring V_{RS}

$$I_T = \frac{V_{RS}}{R_S} = \frac{V_S}{Z_{SS}} = \frac{V_T}{Z_T} \quad (23)$$

Referring to Fig. (7a), the V_S can be given by

$$V_S^2 = (L_2)^2 + (L_3)^2 \quad (24)$$

where $L_2 = V_T - L_1$ and $L_1 = V_{RS} \cos \phi$, so $L_2 = V_{RS} - V_{RS} \cos \phi$ and $L_3 = V_{RS} \sin \phi$. Now, substitute into Eq. (23) to get

$$V_S^2 = (V_T - V_{RS} \cos \phi)^2 + (V_{RS} \sin \phi)^2 \quad (25)$$

Now, the phase angle (α) between the two voltage waves V_T and V_S can, also, be calculated from Fig. (7a), as follows

$$\alpha = \cos^{-1} \left[\frac{(V_T - V_{RS} \cos \phi)}{V_S} \right] \quad (26)$$

Depending on the **Fig. (7a)**, the sum of all phase angles ($\varphi + \alpha + \delta = 90^\circ$). By using Eq. (26), the phase angle (δ) can be expressed by

$$\delta = \left(90^\circ - (\varphi + \cos^{-1} \left[\frac{(V_T - V_{RS} \cos \delta \varphi)}{V_S} \right]) \right) \quad (27)$$

In this method, the sample is presented as a capacitor and a series resistor as in **Fig. (6)**, therefore, $I_T = I_C = V_{CS}/X_{CS}$. Using the **Fig. (7a)**, $V_{CS} = V_S \cos \delta$, as a result the capacitive reactance (X_{CS}) can be found by

$$X_{CS} = \frac{V_S \cos \delta}{I_T} \quad (28)$$

As a result, the capacitance can be given by

$$C_S = \frac{I_T}{\omega V_S \cos \delta} \quad (29)$$

Again, from **Fig. (6)**, $I_T = I_{RES} = V_{RES}/R_{ES}$. Using the **Fig. (7a)**, $V_{RES} = V_S \sin \delta$, thus R_{ES} can be calculated as follows

$$R_{ES} = \frac{V_S \sin \delta}{I_T} \quad (30)$$

The impedance of the sample (Z_{SS}) as presented in RC series circuit (**Fig. (6)**) is just the sum of the impedance of the two elements (R_{ES} and X_{CS}) that is

$$Z_{SS}(\omega) = R_{ES}(\omega) - jX_{CS}(\omega) \quad (31)$$

where the reactance $X_{CS} = [\omega C_S(\omega)]^{-1}$ the mod Z_S can be expressed as:

$$|Z_{SS}| = [(R_{ES})^2 + (X_{CS})^2]^{1/2} \quad (32)$$

The electric conductivity of the samples in the series model (σ_{SS}) can be expressed as

$$\sigma_{SS} = \frac{T}{A[(R_{ES})^2 + (X_{CS})^2]^{1/2}} \quad (33)$$

By using the law of cosine for the triangular in **Fig. (7b)**, the total impedance (Z_T) can be calculated as

$$[(R_S)^2 + 2R_S Z_{SS} \cos(90^\circ - \delta) + (Z_{SS})^2]^{1/2} \quad (34)$$

but $\cos(90^\circ - \delta) = \sin \delta$, so Eq. (34) becomes

$$Z_T = [(R_S)^2 + 2R_S Z_{SS} \sin(\delta) + (Z_{SS})^2]^{1/2} \quad (35)$$

Also, from **Fig. (7b)**, $R_{ES} = Z_{SS} \sin(\delta)$, therefore, Eq. (35) can be written by

$$Z_T = [(R_S)^2 + 2R_S R_{ES} + (Z_{SS})^2]^{1/2} \quad (36)$$

Substituting Eq. (32) into Eq. (36), we get

$$Z_T = [(R_S)^2 + 2R_S R_{ES} + (R_{ES})^2 + (X_{CS})^2]^{1/2} \quad (37)$$

In other one hand, Z_T can be calculated by

$$Z_T = [(R_S + R_{ES})^2 + (X_{CS})^2]^{1/2} \quad (38)$$

Now, $\tan \delta$ can be concluded from **Fig. (7)** and Eqs. (28 and 30),

$$\tan \delta = \frac{V_{RES}}{V_{CS}} = \frac{R_{ES}}{X_{CS}} \quad (39)$$

Impedance functions and conductivity

It is well known that the conductivity is conducted as a function with impedance. It is worthy to mention that, there are several quantities are called immittances: the impedance (Z), admittance (Y), modulus (M) and dielectric constant or dielectric permittivity (ϵ). Where all of them are lined to each other's.

First of them is the admittance (Y),

$$Y \equiv Z^{-1} \equiv Y' + jY'' \quad (40)$$

In the complex domain, the current can be written as $i = v/Z$ or alternatively $i = Yv$, with v is the voltage, where all of them are taken as complex quantities. Practically, Z and Y can be expressed in terms of resistance and capacitance components. In line with, the Z_{SS} of the series RC circuit is subjected as in Eq. (32), while for the parallel RC circuit, the admittance is just the sum of the admittance of the two elements, that is

$$Y(\omega) = G_P(\omega) + jB_P(\omega) \quad (41)$$

Here the subscript P stands for parallel, where the conductance $G_P = 1/R_{EP}$ and the susceptance $B_P = 1/X_{CP}$.

Furthermore, two other quantities are, usually, defined as the modulus (M) function

$$M = M' + jM'' \quad (42)$$

and the complex dielectric constant or dielectric permittivity

$$\epsilon = M^{-1} \equiv \frac{Y}{\mu} = \epsilon' - j\epsilon'' \quad (43)$$

where $\mu \equiv j\omega C_o$ where $C_o = \epsilon_o A/T$ is the capacitance of the empty measuring cell with ϵ_o is the dielectric permittivity of free space, $8.854 \times 10^{-12} F/m$.

The conductivity and dipolar relaxation processes may be present in the same material, and the total conductivity is given by complex electrical conductivity

$$\sigma(\omega) = \sigma'(\omega) + j\sigma''(\omega) \quad (44)$$

the real part of the conductivity is

$$\sigma'(\omega) = \sigma_{ph}(T) + A(T)\omega^{S(T)} \quad (45)$$

where $A(T)\omega^{S(T)}$ is a constant-phase element (CPE) and $\sigma_{ph}(T)$ is a "DC" or frequency-independent part, which is the contribution from the electron-phonon interaction, which is related to the drift of electric charge carriers and follows the Arrhenius relation as given by the relation:

$$\sigma_{ph}(T) = \sigma_0 e^{-\Delta E/KT} \quad (46)$$

where σ_0 is the temperature-dependent conductivity, ΔE is the activation energy of the conduction mechanism, K is the Boltzmann constant and T is the temperature. The imaginary part of the conductivity is

$$\sigma''(\omega) = \epsilon'' \epsilon_o \omega \quad (47)$$

Thus, at low frequencies, a constant conductivity would be seen, but at higher frequencies, a power law contribution enters.

It has been recognized for a considerable time that if the translational invariance of the conductivity activation energy barriers is lost, then the dielectric and conductivity properties become frequency-dependent for a material with no dipolar relaxation processes (ϵ_s is the static dielectric constant is not a function of time), but with a conductivity σ_o , then Eq. (42) becomes

$$Y = \sigma_o + j\omega\epsilon_s\epsilon_o \quad (48)$$

where ϵ_s is given by

$$\epsilon_s = \frac{P_s}{E\epsilon_o} + 1 = \frac{D_s}{E\epsilon_o} \quad (49)$$

where P_s is the total polarization, E is the electric field and D_s is the total electric displacement (defined as the total charge density on the electrodes).

Now, in term of the complex dielectric constant $\epsilon = Y/j\omega\epsilon_o$, Eq. (48) may be rewritten as follows

$$\epsilon = \epsilon_s - \frac{j\sigma_o}{\omega\epsilon_o} \quad (50)$$

Furthermore, the conductivity relaxation time can be defined by $\tau_o = \epsilon_s\epsilon_o/\sigma_o$. Hence, Eq. (50) becomes

$$\epsilon = \epsilon_s - \frac{j\epsilon_s}{\omega\tau_o} \quad (51)$$

Based on the Eqs. (49 and 50), the real $\epsilon' = \epsilon_s$ and the imaginary $\epsilon'' = j\sigma_o/\omega\epsilon_o = j\epsilon_s/\omega\tau_o$. It is also, possible to write Eq. (48) as follows

$$\epsilon = \epsilon_s \left(\frac{j\omega\tau_o + 1}{j\omega\tau_o} \right) \quad (52)$$

The electric modulus formalism $M = 1/\epsilon$ for dealing with conducting materials, for the reasons that it emphasizes bulk properties at expense of interfacial polarization Eq. (52) transforms to

$$M = M_s \frac{j\omega\tau_o}{1+j\omega\tau_o} \quad (53)$$

where $M_s = 1/\epsilon_s$

Conclusion

The Delay-Time measurement method was used to calculate the phase shift (φ) between the two different waveforms using an oscilloscope. The sample of the material can be considered as a capacitor in an AC circuit. Different physics quantities were derived and can be calculated by using the Delay-Time measurement method such as immittances, conductivity and dielectric parameters. The presented method, can be, easy, used from the scientists and engineers.

Author's contributions

Conceived the plan: xx, xy, yz; Performed the experiments: xx, xy; Data analysis: xx yz; Wrote the paper: xx, xy, yz (xx, xy, yz are the initials of authors). Authors have no competing financial interests.

Supporting information

Supporting informations are available from VBRI Press.

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