# The dielectric properties of system composed of insulator-conductor materials

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خواص العزل الكهربائي لنظام متكون من مواد موصلة وعازلة عباس ساهي شريف ، حسين محمد ، محمد غالي محسن جامعة واسط / كلية الهندسة

الخلاصة:

تضمنت الدراسة معرفة الخواص الكهربائية لمادة البولي اثيلين العالي الكثافة والحاوي على تراكيز مختلفة من اسود الكربون ولمدى من التردد المحصور من (١٠٠ هيرتز) إلى (٢٠ كيلو هيرتز) النتائج العملية أظهرت أن إضافة اسود الكربون وبتر اكيز مختلفة إلى مادة البولي اثيلين العالي الكثافة لعينات ثابتة في سمكها يسبب زيادة في ثابت العزل الكهربائي والموصلية الكهربائية المتناوبة وخصوصا في النموذج (.C.B %CL +100 %00) كما اظهرت النتائج ان زيادة السمك للعينات وبنفس التركيز يزيد من ثابت العزل الكهربائي والموصلية الكهربائية بسبب تأثير ظاهرة عزم ثنائي القطب ( The effect of dipole moment )

# Abstract

This study includes investigates the electrical behavior of high density polyethylene (HDPE) having various concentrations of carbon black (C.B.) over a range of frequencies from (100Hz) to (20KHz).Experimental results display that the dielectric constant and a.c. conductivity increase with increasing C.B. concentrations in the samples which have the same thickness but different concentrations, especially in sample (90%HDPE+10%C.B.). The dielectric constant and a.c. conductivity increasing of thickness of samples which have the same concentration of C.B. because the effect of the dipole moment on the sample has large thickness.

# Nomenclature:

ω	Angular frequency	red/sec
v	The applied voltage (potential)	V
С	Capacitance with dielectric	F

C.	Capacitance without dielectric	F
Ι	Total current (I <sub>m</sub> )	А
Ic	Capacitive current (I <sub>mq</sub> )	А
I <sub>mi</sub>	Resistive current	А
€∘	Permittivity of free space	F/m
3	Absolute permittivity	F/m
ź	Dielectric constant	
ε″	Dielectric loss	
<b>6</b> *	Complex dielectric permittivity	F/m
ε <sub>m</sub> *	Dielectric constant of inhomogeneous	
		composite dielectric
ρ	Resistivity	Ω.m
σ	Conductivity	$(\Omega.m)^{-1}$
t	Time	sec
$lpha_{\circ}$	electronic polarizability	$F.m^2$
Pm	Dipole moment	C.m
δ	Loss angle	degree
d	Thickness of the sample	m
А	Area of the sample	$m^2$
$\phi$	Phase angle	degree
Ø	Volume fraction of additive	

### Introduction

Polymers are composed of large molecules. Crystalline polymers such as polyethylene, economically much the most important polymers have long molecules [1] .A molecule of any matter consists of separate (atom or groups of atoms, ions) each having definite electric charge positive or negative. The algebraic sum of all charges in a molecule may be different in various substances. If all positive or negative charges of a molecule are replaced by two equivalent charges one positive and one negative charge mutually equal in absolute magnitude and located at the centers of gravity of separate positive and corresponding separate negative charges, these equivalent charges may either coincide or do not in space. In the case of change coincidence, a non polar molecule exists and the matter composed of such molecules is also called nonpolar. In other case, when even in the absence of an external electric field the molecule is an electric dipole with a non zero electric dipole moment, the molecule is polar just as the matter consisting of such molecules. Then it is obvious that symmetrically arranged molecules (having a center of symmetry)

are non polar. Conversely non-symmetric molecules are always polar [2].Conjugated polymers in the no doped and doped conducting state have an array of potential application in the microelectronics industry. Conducting polymers are effective discharge layers as well as conducting resists in electron beam lithography. They find application in metallization (electrolytic and electroless) of plates through-holes for printed circuit board technology, provide excellent electrostatic discharge protection for packages and housing of electronic equipment. Furthermore, they provide excellent corrosion protection for metals, and may have applications in electromagnetic interference shielding [3].

# Theoretical considerations

# **1-** The complex relative permittivity

If a voltage is applied to an air-filled parallel plate capacitor given as:  $V_c(t) = V_m \cos \omega t$  ....(1) The current will be  $i_c(t) = -\omega V_m C_o \sin(\omega t)$  ....(2) It is convenient to write the voltage as:-  $V_c(t) = \operatorname{Re}[V_m \exp(j\omega t)]$ .....(3)

Where Re denotes the real part of the voltage function, the current will be according to eq. (2)

 $i_{c}(t) = \omega C_{o} V_{m} \cos(\omega t + \pi/2)$ = Re[ $\omega C_{o} V_{m} \exp[j(\omega t + \pi/2)]$ ]  $i_{c}(t)$  = Re[ $j \omega C_{o} V_{m} \exp(j\omega t)$ ]

......(4)

Introducing the quantity:  $I_m = j\omega C_o V_m$ 

.....(5)

Eq. (4) becomes:

 $i_{c}(t) = \operatorname{Re}[I_{m} \exp(j\omega t)]$ .....(6)

V(t) and

 $V_c(t)$  and  $i_c(t)$  may be represented as the projection of rotating vectors on an Argand diagram. In Fig. (l-a) the vector (OA), representing  $V_m \exp(j\omega t)$  has a length |OA | = $V_m$  rotates with an angular velocity ( $\omega$ ) in a counter-clockwise direction, and makes an angle ( $\omega t$ ) with the real axis.

The projection of the vector on the axis  $OQ = OB\cos(j\omega + \pi/2)$  the alternating quantities which differ in phase by  $(\pi/2)$  are said to be in quardrature with one another. By using eqs.(1) and (2), the power supplied to the capacitor, W(t), is given by:

 $W(t) = i_c(t)V_c(t) = -\omega C_o V_m^2 \sin(\omega t)\cos(\omega t)$ 

 $W(t) = -(1/2)\omega C_o V_m^2 \sin(2\omega t) \qquad (7)$ 

From eq. (7), it is clear that the frequency of the power varies at twice the frequency of the applied voltage .The maximum energy stored in the capacitor is given by:

(11)

(13)

In the complex frequency -dependent relative permittivity, both  $\varepsilon'(\omega)$  and  $\varepsilon''(\omega)$  are real function of the angular frequency  $(\omega)$ Thus  $I_m$  has two components, the first:  $I_{mq} = j\omega\varepsilon'(\omega)C_oV_m$ (12) which is quadrature with  $V_m$  and lead it by  $\pi/2$ . The second is given as:  $I_{mi} = j\omega[-j\varepsilon''(\omega)]C_oV_m$  $I_{mi} = \omega\varepsilon''(\omega)C_oV_m$ 

Is parallel to  $V_m$  and said to be in- phase with  $V_m$ . These vectors are indicated in Fig.(1-b).  $I_{mq}$  arises from the reversise charging and discharging of the capacitor. There is no dissipation of energy by the component  $I_{mq}$ , while  $I_{mj}$  is responsible for the dissipation of electrical energy as heat. The time dependent of the current component  $i_q(t)$  which is in quadrature is easily determined from Fig.(1-b) as:

Where:

 $\tan \delta$  is the dissipation factor or loss tangent and is denoted as D.

Now,  $\tan \phi = I_{ma} / I_{mi} = \varepsilon'(\omega) / \varepsilon''(\omega)$ and  $\sin \phi = \varepsilon'(\omega) / |\varepsilon(\omega)|, \cos \phi = \varepsilon''(\omega) / |\varepsilon(\omega)|$ 

Where:

The in-phase component of the current is given by eq.(19). Now the power supplied to the capacitor W(t) is given as:

 $W(t) = (i_{a} + i_{i})V_{c}(t)$ =  $-\omega\varepsilon'(\omega)C_{o}V_{m}^{2}\sin(\omega t)\cos(\omega t) + \omega\varepsilon''(\omega)C_{o}V_{m}^{2}\cos^{2}(\omega t)$ Then, the average of power per one cycle has the value:  $W(t)^{T} = (1/2)\omega\varepsilon''(\omega)C_{o}V_{m}^{2}$  ......(21)

It is convenient to write it<sub>r</sub>as follows:

 $W(t) = 1/T \int W(t) dt \, ,$ 

and the total energy is caused only by the imaginary part of the complex permittivity  $(\varepsilon'(\omega))$ . This means that the in-phase component of the current is responsible for energy dissipation transformed into heat. The origin of

this component  $I_{mi}$  is the dielectric material itself, which may be destroyed, and consequently the capacitor [4].





## 2- The Dielectric constant of mixtures

Practically, it is necessary to deal with the problem of determining the dielectric constant  $(\varepsilon)$  of a composite dielectric which is a mixture of two "or more" components. It is easy to calculate the  $(\varepsilon)$  of a capacitor filled with a dielectric consisting of two different homogenous materials.

For the capacitor with two dielectric arranged in parallel (Fig (2-a)) the equivalent capacitor is:-

 $C^* = C_1 + C_2$ Thus:  $C^* = \varepsilon_1 \varepsilon_0 A_1 / d + \varepsilon_2 \varepsilon_0 A_2 / d$  .....(22)

Where  $\varepsilon_m^*$  is called the dielectric constant of inhomogeneous composite dielectrics and is expressed using the relation above as:

$$\varepsilon_m^* = \varepsilon_1 A_1 / (A_1 + A_2) + \varepsilon_2 A_2 (A_1 + A_2)$$
 (24)

Now replacing the ratio  $A_1/(A_1 + A_2)$  and  $A_2/(A_1 + A_2)$  by  $\phi_1$  and  $\phi_2$  which are the volumes content of the first and second components in the composite dielectric,  $\varepsilon_m^*$  is given by:

 $\varepsilon_m^* = \phi_1 \varepsilon_1^* + \phi_2 \varepsilon_2^* \tag{25}$ 

Also, for the case of series arrangement as shown in Fig.(2-b), the equivalent capacitance  $C^*$  is:-

 $1/C^* = 1/C_1 + 1/C_2$ (26)  $C^* = \varepsilon_m^* \varepsilon_o A/(d_1 + d_2), d_1/d_1 + d_2 = \phi_1, d_2/d_1 + d_2 = \phi_2$ (27)

i.e.:  $1/\varepsilon_m^* = \phi_1/\varepsilon_1 + \phi_2/\varepsilon_2$ or  $\varepsilon_m^* = \varepsilon_1\varepsilon_2/\phi_1\varepsilon_1 + \phi_2\varepsilon_2$ 

In general, for m various composite dielectric eq.(25) and (27) may be as follows:

$$\varepsilon_m^* = \sum_{i=1}^{i=m} \phi_i \varepsilon_i^{'} \qquad (28)$$
$$(\varepsilon_m^*)^{-1} = \sum_{i=1}^{i=m} \phi_i / \varepsilon_i^{'} \qquad (29)$$

However, in most of practically important cases, composite dielectrics, such as, plastic compounds with fillers, are statistical mixtures of several compounds. In such cases eq.(28) and (29) are considered unsuitable .The true value of the dielectric constant of statistical mixture should lie between the value determined by eq.(28) and (29) which is known as the Wiener inequality [2].



(30)

# **Experimental Procedure**

The test samples were prepared with the objective of the doping HDPE with C.B. is to modify the dielectric properties of neat HDPE.HDPE is an insulating polymer, while C.B. is a conducting semimetal microscopic . The HDPE and C.B. as powder have grain size selected between  $(45\mu m - 150 \mu m)$ . The powders were throughly mixed by using lie speed electrical mixer operated for (30 min) to ensure homogeneity of mixing. The powders were weighted accurately using an electronic digital balance with resolution of (10 mgm).

After mixing, the weighed powders were placed into the die of the mounting press. The pressure was adjusted to (1 MPa) and the temperature to (100 C°). This specific temperature was chosen after several trial tests because of difficulties encountered in removing the prepared samples from the die at higher temperature, although the melting temperature of HDPE is about (127 C°). The test samples were circular plates of (32 mm) in diameter and (2.5mm) in thickness. All the dielectric measurements were carried out using an experimental test system shown schematically in Fig.(3). It provides automatic simultaneous measurement of dissipation factor (tan  $\delta$ ) and capacitance at different frequencies. A programmable LCZ meter (HP 4276 A) provides direct measurement of (tan  $\delta$ ) and capacitance, where from the later the dielectric constant, is calculated. The LCZ meter provides spot test signals in the frequency range (100 Hz -20 KHz) with step change of (100Hz).



### **Results and Discussion**

The determining values of Dielectric constant over a frequency range of (0.1-20)kHz is shown in Fig.(4). This figure shows that the dielectric constant increases with increasing concentration. The increase can be attributed to an increase in the number of Dipoles in the sample since the dielectric constant is directly proportional to the total dipole number, and consequently to the total dipole moment which equals the number of dipoles per unit volume multiplied by the magnitude of each dipoles moment[6]. In addition Fig.(4) shows a relative decrease in the dielectric constant with frequency which is explained as a dielectric introduced into an electric field undergoes polarization. This

phenomenon known as dielectric polarization [7]. The dielectric constant is related with polarization. In general, as the frequency of the applied field is increased a point is reached where the molecules of a material can no longer rotate fast enough to remain in phase with field. Consequently, the contributions of the interfacial and molecular polarization mechanisms to the net polarization decline, which subsequently causes reduction in the magnitude of the dielectric constant [8],[9]. The dielectric constant which related strictly with real part of permittivity, therefore, increase with increase of () [10]. This cause represented by Fig.(5).In Fig(6) shows a plot of A.C conductivity as a function of frequency for samples containing different C.B. concentration incorporated in HDPE. This figure shows that the A.C. conductivity increasees linearly or nearly linear with frequency in accordance with eq.[11]:

 $\sigma(\omega) = \varepsilon^{"}(\omega)\varepsilon^{\circ}\omega \qquad (31)$ 

The conductivity is mainly determined by the many paths of percolating clusters rather than the small effect of the capacitors. Therefore, the conductivity of the sample will not change significantly up to a certain frequency above which the contribution of the capacitance becomes important. As the frequency increases the current passing through each capacitor increases resulting in increased conductivity of the sample [12]. According to the above details Fig.(7) represented the imaginary part of permittivity for different samples vs. the frequency.

The Figs.(8),(9) represented the dielectric constant and A.C. conductivity vs. frequency for samples have different thickness but the same concentration. In sample of (5 mm) which have values of dielectric constant and A.C. conductivity larger than (2.5 mm) the reason for this cause related with dipole moment which induced by the field as result of an elastic displacement of the electronic charge distribution relative to the nucleus. The included dipole moment may be represented by:

 $P_m = \alpha_o E$  .....

(32)

Where is called the electronic polarizability of the atom. Therefore, in sample of (5 mm) the dipole moment is larger than in sample (2.5) which government on the value of dielectric constant and A.C. conductivity [11].



Fig.(4): Dielectric constant vs. Frequency for Different samples of (2.5 mm) at (25 C<sup>0</sup>)



Fig (5): Real part of permittivity vs. Frequency for different samples at (25  $C^0$ )





Fig(6):A.C. conductivity vs. frequency for different samples at  $(25 \text{ C}^0)$ 



)Fig (7):Dissipation factor vs. Frequency for different samples at (25  $C^0$ 







# **Conclusion:**

From the above discussion, we can conclude the following:

1- The dielectric constant of HDPE increased by adding C.B. especially in the specimen which have (90% HDPE +10% C.B.). The high value at (1 KHz) is equal to (1242.26).

2- A.C. conductivity for HDPE –C.B.0 composite increased to very high value at specimen (90% HDPE +10% C.B.).

3- The dissipation factor of HDPE increased by adding the C.B.

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