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Measurement of Complex Impedance at High AC Voltages using Waveforms

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Abstract *– We present the application of a waveform technique in determining the complex impedance of dielectric composite films at high AC voltages using a DAQ card and virtual instrumentation. Impedance characterization near dielectric breakdown conditions was performed for composites with enhanced dielectric properties. Dielectric hybrid materials made of organic resins and high dielectric constant modifiers under high AC voltages demonstrated fundamentally different behavior than the conventional fiber-glass reinforced epoxy resin laminates.*

Keywords *– Waveform Measurements, Complex Impedance, Dielectric Hybrid Materials*

I. INTRODUCTION

Thin dielectric composite films with enhanced electrical and mechanical properties are used in electronics as building blocks of functional circuits and as the insulation materials for power distribution. The electrical performance of these materials can be evaluated by measuring the dissipation current, break down voltage and / or dielectric loss tangent. The conventional standard testing procedures that are currently in use, have been developed for thick high-impedance dielectrics [1] and measure performance in terms of breakdown voltage. Since the impedance of thin dielectric films and those with a high dielectric constant is rather low, conventional measurement procedures are inadequate and may lead to ambiguous results.

The conventional testing techniques use either DC or AC current [2]. However, AC testing voltage is preferred, especially in the case of asymmetric metal-insulator configurations, which may have rectifying characteristics, and for ferrolectric composite materials that may exhibit polarization reversal. Under AC high field, the response of nano-structured materials may be non-linear. Monitoring and analysis of both the incident voltage and the resulting current waveforms is more useful for proper evaluation. Vankatesh and Naidu used a capacitance divider and a digital storage oscilloscope to capture waveforms [3]. Tanaka and coworkers developed a system that monitors the dissipation current waveforms for a capacitive load using a capacitance bridge and a digital oscilloscope [4, 5]. To date no published successful attempt has been made to measure complex impedance and the phase component of the dissipation current as a function of a high AC voltage.

In this paper, we describe a measurement technique for recording and analysis of the incident voltage and the resulting dissipation current waveforms using a multi channel Data Acquisition (DAQ). We apply this technique to determine the complex impedance of dielectric films at high AC voltages. The effect of high voltage on the electrical performance of materials is demonstrated for conventional glass-fiber epoxy resin laminates and for novel composites with enhanced dielectric properties.

II. EXPERIMENTAL SETUP

The availability of computerized data acquisition systems makes it convenient to record a digitized spectrum of the entire voltage wave as a function of time. In contrast to the conventional procedures that utilize engineering notation, recording the voltage waves and transforming the data from the time domain to the frequency domain enables determination of phase between the voltage and the current waves and consequently, the complex impedance, $\vec{Z}$. Figure 1 shows the block diagram of the measurement system. An IEEE 488.2 bus is connected to a computer to control the instruments using Standard Command for Programmable Instruments Language. An IEEE 488.2 controlled function generator (Stanford Research Systems DS345) is used to

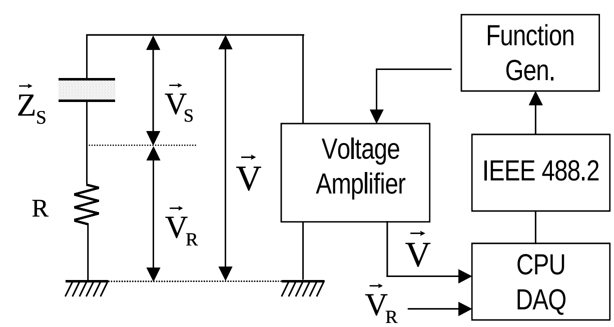

Fig. 1. Measurement diagram

source a sinusoidal voltage wave at frequency, *f*, of 50.000 Hz. The source voltage wave is amplified by an operational voltage amplifier (Trek Model 610C), and a high AC voltage is applied to the specimen. The specimen current is monitored using a standard reference resistor R as shown in Fig 1. Separate channels of the data acquisition (DAQ) card record the waveform of the monitoring signal (which is proportional by a gain factor to the output voltage, $\vec{V}$, from the voltage amplifier), and the voltage wave at the reference

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resistor, $\vec{V}_R$ (which is proportional to the specimen current). We used a 16 bit analog-to-digital converter (NI-6034E) clocked at a frequency of 100 kHz. The sampling was assumed coherent i.e. containing an integer number of the sine-wave periods and an integer number, *N*, of the data points. The discrete quantization time and amplitude errors [6] were assumed to be within the manufacturer's specification for NI-6034E.

The experimental uncertainty in $\vec{Z}$ depends primarily on the tolerance of the reference resistor and its phase characteristic, and the corresponding uncertainty of $\vec{V}_R$. The combined relative uncertainty was 0.5 % for the impedance magnitude and 1.5% for the impedance phase.

III. ANALYSIS

In the time domain, the voltage and the current alternating at frequency, *f*, are periodic functions of time, *t*, that can be expressed as waveforms $v(t)= v_o \cos(\omega t+\varphi)$, and, $i(t)=(v_{Io} /R) \sin(\omega t)$, where v_o is the voltage amplitude, (v_{Io} /R) is the current amplitude, $\omega=2\pi f$, and φ is the phase angle between the voltage and the resulting current flowing through a reference resistor *R*. In engineering notation, the root-mean-square (rms) or effective voltage and current are defined as $V = v_o / \sqrt{2}$ and $I = (v_{Io} /R)/ \sqrt{2}$ respectively. However, in the case of complex loads such as capacitance, *C*, or inductance, *L*, there will be a phase shift, φ, between *V* and *I*. In general, the alternating voltage and the current can be expressed as phasor transforms from the time domain to the frequency domain, representing complex quantities, each having an amplitude and phase. The quotient of the voltage phasor $\vec{V}$ and the current phasor $\vec{I}$ represents the complex circuit impedance $\vec{Z}$. A waveform digitized to *N* points, where v(*l*) represents an individual voltage data point recorded at the time $t_l = (2\pi l)/(\omega N)$, can be expressed as a sum of the phasor components V' and V":

$$v(l)=V'\cos(2\pi l/N)+V''\sin(2\pi l/N)) \quad (1)$$

Using the digital Fourier transform technique (DFT) [6] the wave can be transferred from the time domain to the frequency domain by calculating V' and V" from (2) and (3):

$$V' = \frac{2}{N}\sum_{l=1}^{N} v(l)\cos\left(-\frac{2\pi l}{N}\right) \quad (2)$$

$$V'' = \frac{2}{N}\sum_{l=1}^{N} v(l)\sin\left(-\frac{2\pi l}{N}\right) \quad (3)$$

The phasor amplitude, V_0, and its initial phase angle, δ_0, in the frequency domain representation of the waveform, can be calculated from (4) and (5) respectively [7]:

$$V_0 = \sqrt{(V')^2 + (V'')^2} \quad (4)$$

$$\delta_0 = \arctan(V'/V'') \quad (5)$$

The applied voltage, $\vec{V}$ can be expressed in exponential notation by (6):

$$\vec{V} = V_0 \exp(i(\omega t + \delta_0)) \quad (6)$$

where the initial phase δ_0 is given by (5).
Similarly, the voltage $\vec{V}_R$ can be determined using expressions (2) – (5) and represented in exponential notation:

$$\vec{V}_R = V_{R0} \exp(i(\omega t + \varphi + \delta_0)) \quad (7)$$

$$\varphi + \delta_0 = \arctan(V_R'/V_R'') \quad (8)$$

where φ is a phase shift between $\vec{V}$ and $\vec{V}_R$.The complex impedance of the specimen, $\vec{Z}_S$, can be obtained from (9).

$$\vec{Z}_S = R\left(\frac{\vec{V}}{\vec{V}_R} - 1\right) \quad (9)$$

Having determined the complex $\vec{Z}_S$, one can perform further analysis of the material's linear and non-linear dielectric properties such the dielectric loss tangent and the dielectric constant as a function of the specimen voltage, $\vec{V}_S = \vec{V} - \vec{V}_R$. The DFT, and all the complex algebra calculations can readily be accomplished within a framework of integrated virtual instrumentation software, such as VEE from Agilent, LabView from National Instruments or Matlab from MathWorks.

IV. RESULTS AND DISCUSSION

In order to verify the proposed procedure experimentally, we implemented the experimental set-up shown in Fig 1 and performed impedance measurements on several fiber-glass reinforced epoxy resin laminates, as well as on newly developed hybrid materials with enhanced dielectric properties. Here we present results obtained for a 50 μm thick FR-4 epoxy resin laminate and for a 40 μm thick dielectric composite made of an organic resin filled with ferrolectric ceramics sub-micron particles. Both materials are representative of high capacitance layers that are being used in advanced electronic circuits for power-ground de-coupling. The test pattern was made with a diameter of the top electrode of 14.1 mm, in accordance to the ASTM standard [1]. Figure 2a shows an example of typical waveforms obtained for the FR-4 samples at 50 Hz. The response waveform is a corresponding sinusoid of the specimen voltage. There is no indication of non-linear or rectifying

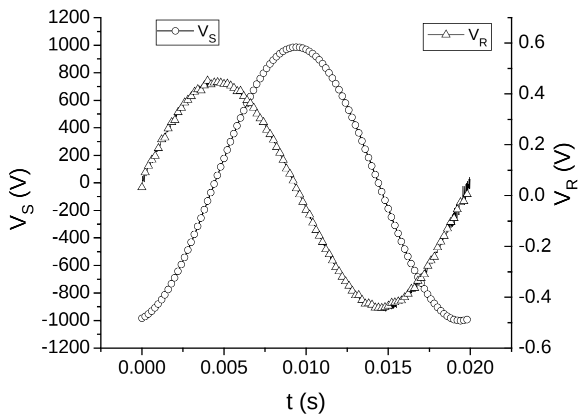

Fig. 2a. Voltage waveforms for FR-4 specimens: circles -V_S, -triangles - V_R, R= 10000.0 Ω.

effects. Since the time lag, τ_0, between $\vec{V}_S$ and $\vec{V}_R$ is about - 5 ms, the phase shift, ($\varphi = 2\pi f\tau_0$) is about - 90° indicating that the FR-4 sample has a capacitive character. Figure 2b illustrates impedance and phase plots as a function of the specimen voltage.

The impedance magnitude remains at a level of about 22.3 MΩ up to 1.7 kV. Above 1.7 kV, the impedance starts to decrease, which is accompanied by an increase of the phase factor. Such a change of phase indicates that the character of

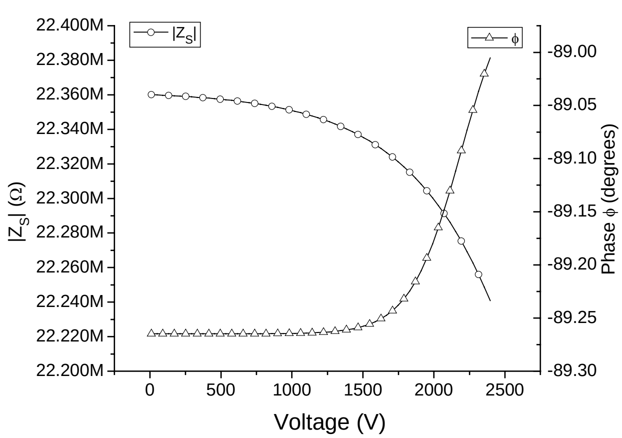

Fig. 2b. Impedance magnitude (circles) and phase angle (triangles) obtained for FR-4 specimens.

the specimen changes above 1.7 kV from capacitive to more resistive. The voltage withstanding condition may be attributed to a voltage range where the impedance characteristic remains insignificantly affected by the applied voltage. The presented results demonstrate that such a condition can be inferred from Fig. 2b without ambiguity.

Figure 3a shows voltage waveforms that are representative for the high k composite films.

A distortion in the $\vec{V}_R$ waveform is caused by a non-linear response generated by polarization reversal in the ferroelectric component dispersed in the organic resin phase.

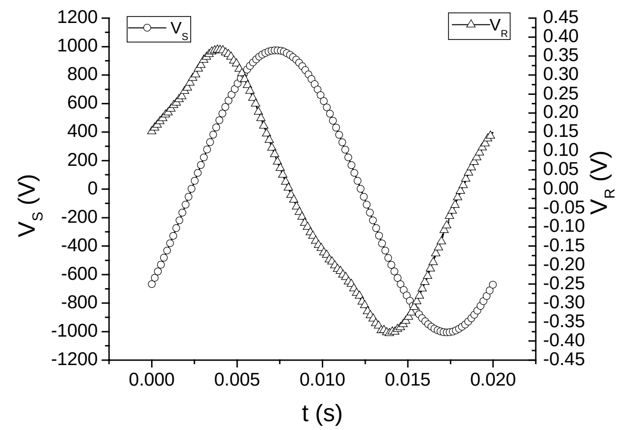

Fig. 3a. Voltage waveforms for high dielectric constant composites (k=12): circles -V_S, -triangles - V_R, R= 1000.0 Ω.

Figure 3b shows that, in comparison to FR-4 films, the impedance of the high-k films decreases considerably with increasing voltage. The drop in impedance is accompanied by a significant change in phase. Under the applied electric field, the material undergoes a reversible transformation from

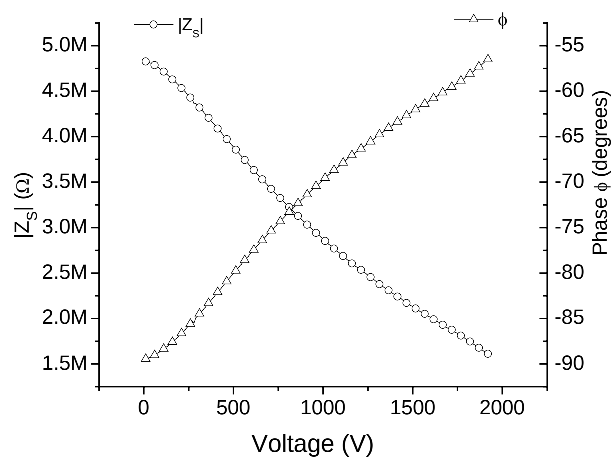

Fig. 3b. Impedance magnitude (circles) and phase angle (triangles) of high dielectric constant composites (k=12).

dielectric to resistive. Besides changing functionality, at a sufficiently high power level, such behavior may lead to thermal run-away due to excess of dissipated current. This mechanism is fundamentally different than the dielectric breakdown that occurs in typical dielectric materials, where the dielectric failure is due primarily to voltage excited avalanche ionization. It should be noted that the presented procedure of recording and analyzing waveforms allows the evaluation of specific characteristics of materials that cannot be readily evaluated with conventional techniques. This measurement procedure is especially suitable for detecting and analyzing non-linear dielectric effects that can result from polarization reversal and rectifying barriers. Such effects may appear at relatively low voltages in nano- sized interfaces, composites and sub-micron thin dielectric films that are of interest to new technologies. In industrial practice, AC high voltage testing is performed at either 50 Hz or 60 Hz. The implemented instrumentation is capable of operating at frequencies of up to about 100 kHz. In general, the presented theoretical analysis is based on the assumption of quasi-static conditions, where the circuit consists only of lumped elements. Therefore equation (9) is not-valid at higher frequencies where the propagation effects may not be neglected i. e. the length of the propagating wave is comparable with the size of the circuit elements.

V. CONCLUSION

We demonstrated a waveform technique to measure complex impedance of dielectric films at high AC voltages by recording and analysis of the incident voltage and the resulting dissipation current waveforms using a multi channel Data Acquisition (DAQ). This procedure is capable of resolving the phase component between the specimen voltage and the specimen current and thus is suitable for determining the specimen complex impedance. In contrast to the circuit voltage and current parameters, the impedance of a material reflects its properties directly. Therefore, this method can be used to study the relationship between the structure and properties of new materials and to determine the mechanism of their dielectric breakdown.

DISCLAIMER

Certain commercial materials and equipment are identified in this paper in order to adequately specify the experimental procedure. This does not imply any recommendations by the National Institute of Standards and Technology nor does it imply that these materials or procedures are the most suitable for these purposes.

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