Development of Experimental Device for Frequency Dependence of Electro-Physical Properties of Highly Conductive Dielectrics Based on Three-Voltage Method

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DOI: https://doi.org/10.51584/IJRIAS.2025.1010000018

Received: 10 Sep 2025; Accepted: 17 Sep 2025; Published: 28 October 2025

ABSTRACT

In the case of highly conductive dielectric materials such as water and other aqueous liquids, semi-conductive stress grading materials, etc., there are some difficulties and limitations in measuring their electro-physical parameters using the measurement methods and conventional metal electrodes. This paper describes the development of an experimental device capable of measuring dielectric permittivity and dielectric loss tangent of the above-mentioned highly conductive dielectric materials in the comparatively wide frequency range of power frequencies to 1 MHz, the principle of which is based on the three-voltage method; and also, it has been dealt with how to design the hardware and software. The operating characteristic and reliability of the designed and manufactured experimental device were verified through the simulation by using electrical equivalent circuit method and comparing with the measurement data for the standard experiment device.

Keywords: Lossy dielectrics, Electro-physical property, Three-voltage measurement method, Frequency dependence

INTRODUCTION

Most of materials, such as various inorganic, polymeric materials and their composites, semi-conductive stress-grading materials, water and aqueous solutions, etc. are non-conductive ones from the viewpoint of electro-physical properties. Since the electro-physical properties of these dielectric materials are closely related to their internal information, including their chemical structures, composition, molecular bonding and mobility, the electro-physical measurement techniques have long been widely applied in practice[2,3]. In industrial practice, there exist not only high-resistivity dielectrics whose conductivity is quite close to zero like electrical insulation materials, but also do high-conductivity dielectric materials such as water and various aqueous solutions, semi-conductive stress-grading dielectrics. Because of the high conductivity, it is difficult and limited to measure the electro-physical properties of the above-mentioned highly lossy dielectric materials by using the same methods and contact-type metal electrodes as those of high resistivity dielectrics.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

For example, when the dielectric sample is highly conductive, it may be difficult to adjust both the equilibrium state of the electrical components in the bridge method and the LC resonance state in the Q-meter method. Therefore, it is of theoretical and practical importance to develop a device capable of measuring the electro-physical parameters of various high-conductivity dielectric materials widely used in various industrial applications.[1-7]

This paper aims to introduce the development of an experimental device capable of measuring the dielectric permittivity and dielectric loss tangent of highly conductive dielectric materials in the frequency range of power frequencies to 1 MHz based on the three-voltage method.[11]

Measurement and operation principles of device

In general, the permittivity and dielectric loss tangent values of a dielectric sample can be obtained from the impedance measurements of the sample. The impedance of a dielectric sample is determined by the ratio of the AC voltage applied across the sample to the AC flowing through it (Fig1). In Fig 1, Z_X is the impedance of the electrode system containing the dielectric sample.

The equivalent circuit and vector diagram for realizing the measurement principle diagram shown in Fig 1 are given in Fig 2. In Fig 2(a), the resistance R plays the role of sensing the current flow through the dielectric sample considered.[9, 12]

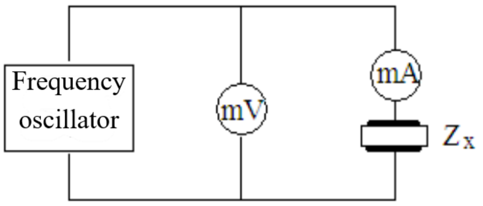


Fig 1: The principle diagram for measuring electrical impedance of dielectric sample

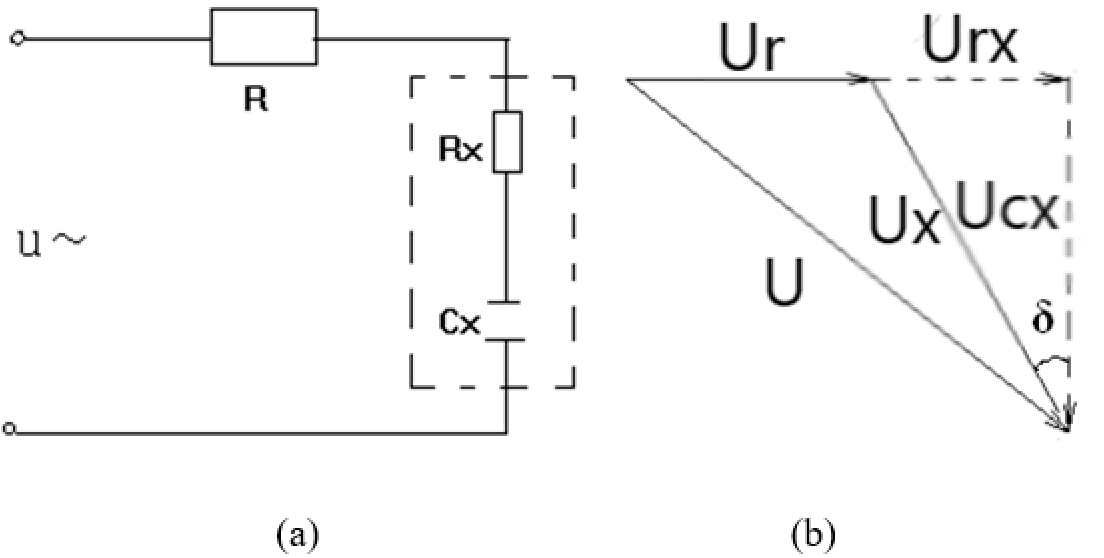


Fig 2: The principle of a highly lossy dielectric (a) Equivalent circuit (b)Voltage vectors

According to dielectric theory, it is known to be reasonable to use the equivalent circuit of the capacitance C_X and the resistance R_X in series for a highly lossy dielectric sample.

From the voltage vector diagram shown in Fig 2(b) corresponding to Fig 2(a), the capacitance C_X and the tangent of the dielectric loss angle tanδ of the highly lossy dielectric sample under consideration at an arbitrary frequency condition can be obtained from the following equations:

$$C_x = \frac{U_r}{2\pi f\ RU_x \cos\delta} \qquad (1)$$

Here, C_X-sensing capacity, f-frequency, R-resistance value, U_x-voltage for C_X, U_r-voltage for R_X, $\cos\delta$-cosine of δ

$$\tan\delta = \frac{1}{\sqrt{\left(\frac{2U_rU_x}{U^2 - U_r^2 - U_x^2}\right)^2 - 1}} \qquad (2)$$

As can be seen from Equation 1 and Equation 2, the electro-physical properties of a highly conductive dielectric can be easily obtained by only measuring the input alternating voltage U, the voltages U_r and U_x applied across the current-sensing resistance and the dielectric sample electrode, respectively in the equivalent circuit given in Fig 2.

Hardware and software configuration

Circuit configuration and operating principle of the hardware

The hardware of the experimental device for measuring the electro-physical properties of a highly lossy dielectric consists of power supply unit, negative voltage output unit, oscillation control unit, main control unit, voltage measurement unit, communication unit, keyboard input unit, current-sensing resistance selection unit, display unit and quartz crystal oscillation unit.

In this hardware, the alternating voltage of any desired frequency is applied to the input of the circuit of the current-sensing resistor and dielectric sample electrode in serial by a harmonic oscillator AD9833 controlled by a microprocessor Atmega32.

The hardware is equipped with three measuring units in total, including the units of measuring the voltages applied across the sample electrode, current-sensing resistance and circuit input, respectively.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

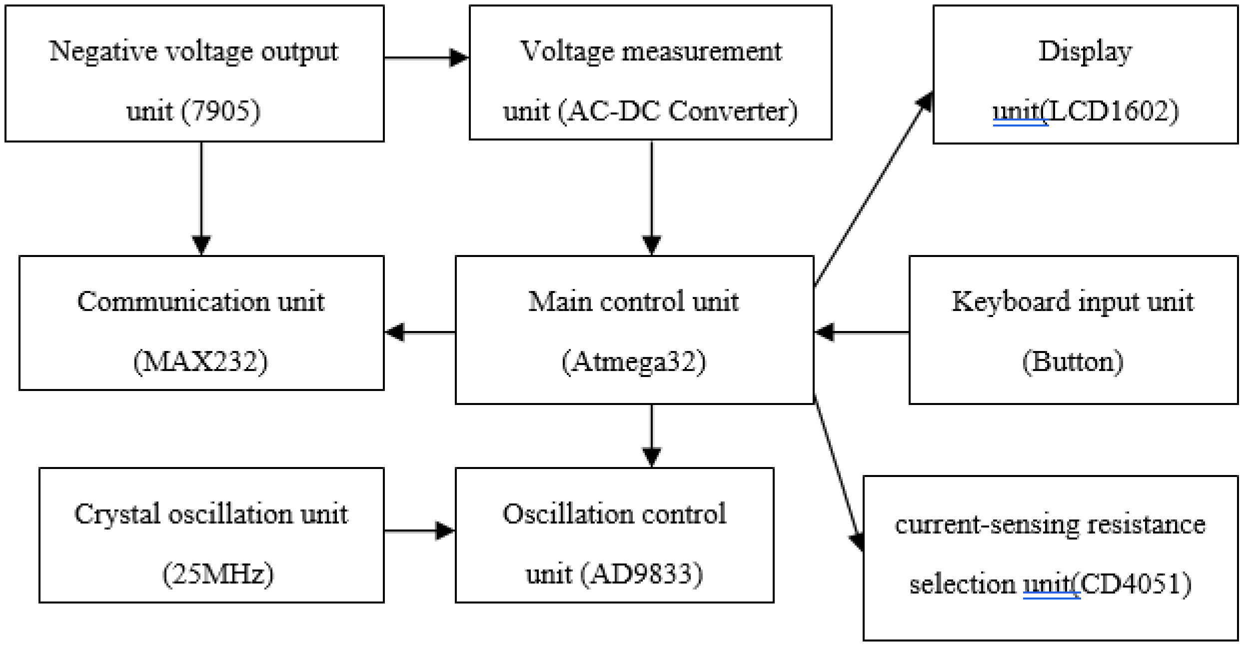


Fig 3: The block diagram of the hardware circuits

In the microprocessor, the voltage measurement values are simultaneously received from these three measuring units, and analyzed by using AD conversion.

And also, this hardware is equipped with a communication unit embedded, which is centered on MAX232, enabling RS-232 communication with the personal computer, and sends the data from the personal computer to the microprocessor.

In the personal computer interface, the detailed parameters of the frequency of the voltage to be applied to the circuit are set and sent to the microprocessor.

In order to obtain the tangent values of the dielectric loss angle of the sample in a certain frequency range, the frequency range should be set, with the starting point, endpoint and frequency rise values set at the personal computer interface, and then transmitted to the microprocessor.

LabVIEW is chosen as the software development platform for the hardware control of experimental device

Microprocessor control software

Microprocessor control software consists of the data communication receiver, data communication transmitter, voltage data analog-to-digital converter, voltage measurement, SPI communication, AD9833 control, LCD display, transfer function, additional resistance option, voltage measurement and transmission command, frequency interval setting command, experiment executive, keyboard usage command, and main program executive.

ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

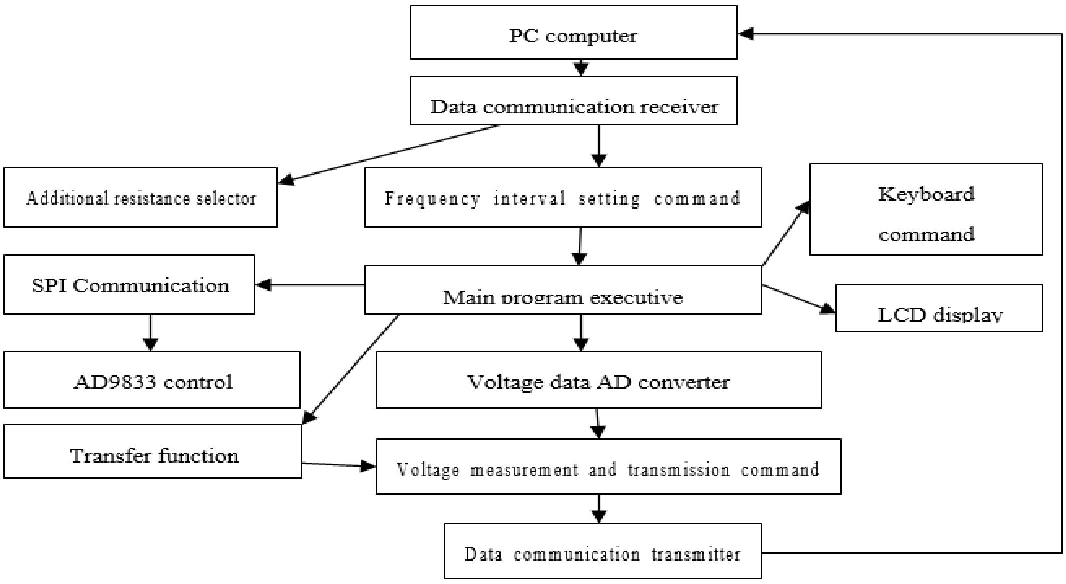
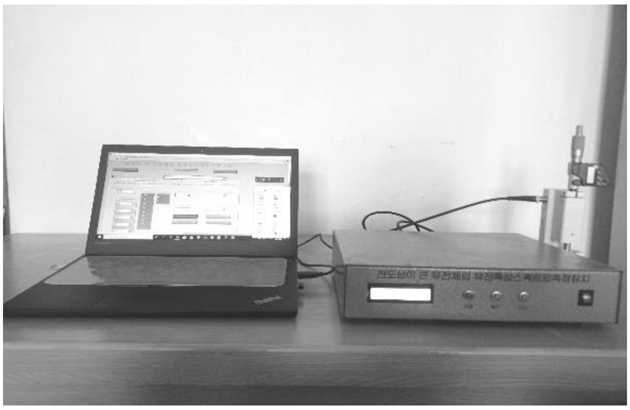


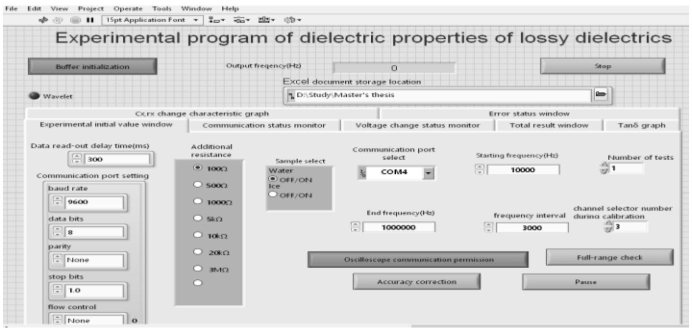
Fig 4: Microprocessor block diagram

Verification of Device performance

Fig 5 shows the photographs of the real object and PC interface of the electro-physical experimental device for highly conductive dielectric materials.



(a)



(b)

Fig 5. Experimental device (a) Hardware (b) PC interface

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN APPLIED SCIENCE (IJRIAS)
ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

For the purpose of verifying the performance of the experimental device shown in Fig 5, an equivalent sample consisting of known resistance R and capacitance C in serial was used instead of the dielectric sample shown in Fig 1.

The performance of the experimental device developed was verified by comparing the experimental values of the capacitance and resistance obtained using the aforementioned three-voltage method with the known C and R values of the equivalent circuit sample (Table 1).

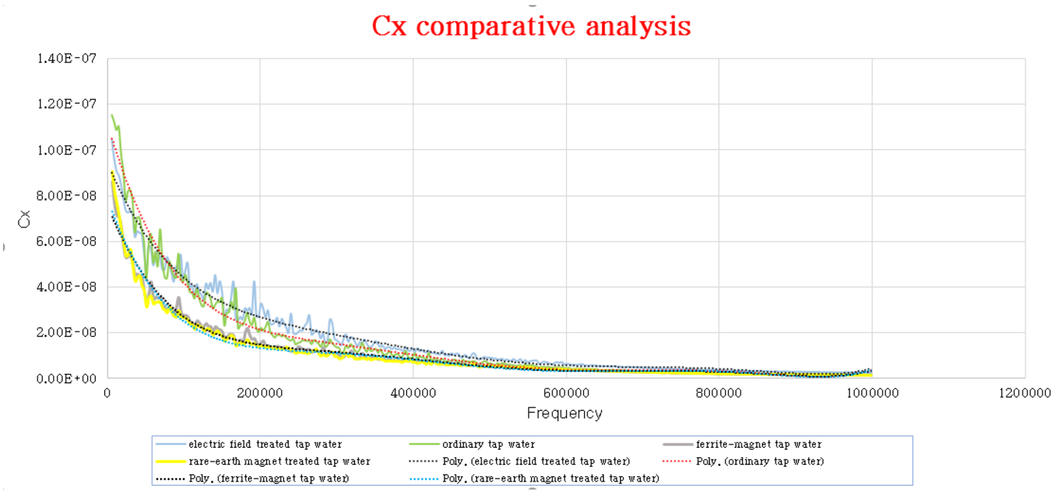
Table 1. Results of the device performance verification.

Measurement frequency (Hz)	Equivalent circuit parameter values		Experimental values	
	C(F)	R(Ω)	C(F)	R(Ω)
60	4.8E-07	5251	4.94E-07	5408.5
400	2.9E-07	1379	2.98E-07	1420.3
6310	8.89E-08	283	9.15E-08	291.4
158500	4.8E-09	209	4.94E-09	215.2
1,000,000	7.52E-10	210	7.74E-10	216.3

Fig 6 shows the measurement results of the frequency dependences of capacitance and dielectric loss tangent of tap water in the frequency range of 10 Hz to 1 MHz.

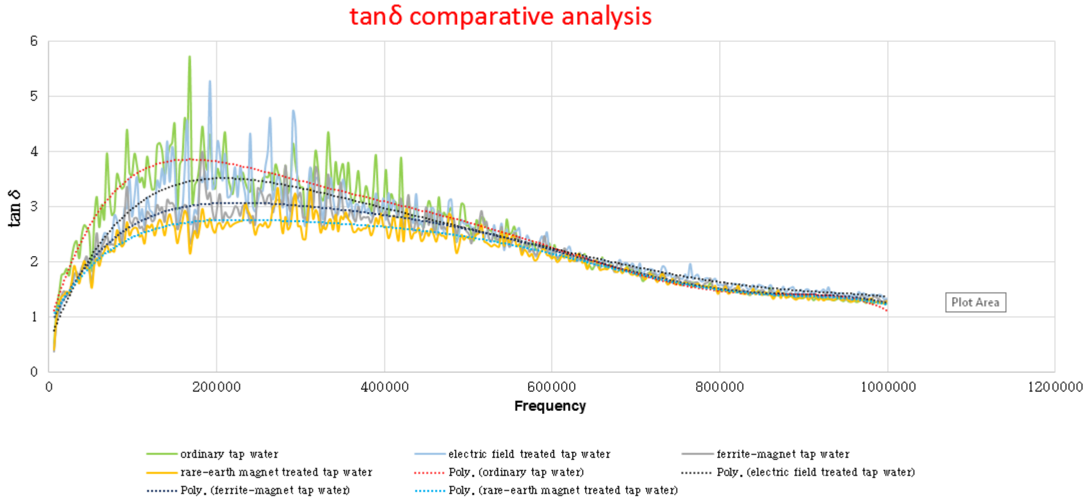
And also, the experimental data obtained for the tap water, one of typical high lossy dielectric materials using the aforementioned three-voltage method were compared with those obtained using the well-known impedance analyzer Solartron-1260(Table 2).

From the results of the measurement experiments, the following conclusions can be drawn:



ISSN No. 2454-6194 | DOI: 10.51584/IJRIAS |Volume X Issue X October 2025

(a)



(b)

Fig 6: Result of Experiment device(a) Capacitance-frequency (b) tanδ-frequency

Table 2. The capacitance and dielectric loss tangent values of tap water

obtained using three-voltage method and Solartron-1260

Measurement frequency (Hz)	Three-voltage method		Solartron 1260	
	C(F)	R(Ω)	C(pF)	R(Ω)
100	4.33E-07	3893	4.21E-07	3780
1,000	2.28E-07	739	2.22E-07	718
10,000	6.47E-08	260	6.29E-08	253
100,000	7.78E-09	216	7.56E-09	210
1,000,000	7.76E-10	217	7.54E-10	211

First, the experimental device based on the three-voltage method can be effectively used for the measurement of electro-physical properties of highly lossy dielectric materials in the frequency range below 1 MHz.

Second, too high and low conductivity of the lossy dielectric material considered may make it difficult to apply the three-voltage method mentioned in this paper.

CONCLUSION

This paper has been dealt with the development of an experimental device capable of measuring the frequency variation characteristics of electro-physical parameters of highly conductive dielectric materials, including water, aqueous solution and semiconducting stress-grading dielectric materials in the comparatively wide frequency range below 1MHz.

As mentioned above, the experimental device based on the three-voltage method can be effectively used for the evaluation of the electro-physical properties of highly conductive dielectric materials and monitoring of production processes, which may be widely used in light industry, agriculture, construction and other fields as well as the electrical industry.

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