New Statistical Methodology for Capacitor Data Analysis via LCR Meter

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Abstract: This research work introduces a novel methodology to establish the relationship between capacitance and resistance when dealing with imprecise data obtained from LCR meters. The proposed relationship is based on the principles of neutrosophic statistics, enabling the utilization of interval data of resistance or capacitance without losing the indeterminacy of the intervals. By employing this relationship, we can accurately determine capacitance values from interval data of resistance, thereby generating more flexible and informative graphs. Additionally, we have applied the neutrosophic analysis method to the interval data of resistance to further enhance our findings. The comparative analysis demonstrates the superiority of the proposed approach and neutrosophic analysis over classical or pre-existing methods, highlighting their enhanced flexibility and information content.

Keywords: LCR meter; Resistance; Capacitance; Informative.

1. Introduction

Energy storage devices have been gotten importance at the industrial level in recent years. This thing has increased the fabrication of energy storage devices such as batteries and supercapacitors etc. Generally, highly efficient and flexible fabrication of such energy storage devices is always required. For example, if we talk about supercapacitors, a number of research have used different materials in the fabrication of highly efficient supercapacitors. To understand the behavior of the supercapacitor different models have been like transmission line model [1], thermal, frequency, and voltage model [2], two branch model [3], resistance and capacitance comparison models [4, 5]. These all have different efficient ways to study the supercapacitors behavior. Similarly, there are three methods used for the measurement and observation of the capacitance of the supercapacitors like impedance spectroscopy [6], galvanostatic charging [7], digital meter (like LCR meter) [8] and cyclic voltammetry [9]. Generally, it is seen that through impedance spectroscopy one can gets a differential capacitance but through galvanostatic charging and cyclic voltammetry one can gets integrate experimental value of capacitance [10]. Similarly, through the digital meters especially LCR meter we get the imprecise value of capacitance i.e. in interval form [11-15]. If we talk about the data analysis of supercapacitors in term of material statistics, there are two methods for data analysis. One is classical method (based on classical graphs, tables and formulas of analyzing) which is used when data is single value. For example the use of classical table to represent the data of ultra-capacitor's capacitance can be seen in following reference [8] Table 1. The classical method of analysis is good when some one is dealing with the fix-point/deterministic data. But if there is interval/indeterministic data, the classical method is not used directly untill the indeterministic data is not convered into deterministic. For example, generally, research takes the average of a interval and used in their work.

In this way, the variance of interval turn in to a fix value as the result a person will not able to analyze the whole variance of data (may be capacitance or resistance) for that interval. That's we turn to the indeterministic model. This model is based on the neutrosophic statistics. Neutrosophic statistics is a tool or method of statistics which is used to analyze the interval value without losing the indeterminacy of each interval. It was proposed by F. Smarandache, which is more flexible and informative then all other methods of the statistics. Recently, it is observed that the use of the neutrosophic statistics has been increased in different field like in medicine to analyze diagnosis data [16], in applied sciences [17], in astrophysics to analyze the wind data [18] and in material science for sensor data analysis [12], conductor resistance analysis [11] and graphene foam analysis [19].

1.1 Aim of Study

This research endeavors to develop an innovative indeterministic relationship between capacitance and resistance in LCR data measurement, with a specific focus on supercapacitors and sensors. Leveraging principles from materials statistics, we employ the neutrosophic statistics framework to formulate the proposed relationship. By using this indeterministic approach, we aim to directly calculate capacitance from interval values of resistance and vice versa, enabling more accurate and comprehensive characterizations of these electronic devices. Through the incorporation of materials statistics and the application of the neutrosophic framework, we anticipate significant advancements in materials science and electronic engineering analyses.

2. Methodology

The present study introduces an innovative Indeterministic model for capacitance and resistance, firmly rooted in the principles of neutrosophic statistics. This model will be instrumental in accurately calculating capacitance and resistance from interval data. Before delving into the details of our proposed approach, let us explore some of the prior definitions and concepts of neutrosophic statistics:

2.1 Definition of Neutrosophic Statistic

Let X_N is a neutrosophic variable with interval of variance $X_N \in [X_L, X_U]$ having size $n_N \in [n_{NL}, n_{NU}]$ with indeterminacy $I_N \in [I_{NL}, I_{NU}]$, so the neutrosophic formula can be written as written as follows [20]:

$$X_{iN} = X_{iL} + X_{iU}I_N \ (i = 1, 2, 3, \ldots, n_N) \tag{1}$$

$X_{iN} \in [X_{iL}, X_{iU}]$ has two parts: X_{iL} expressing the lower value which is under classical statistics and $X_{iU}I_N$ is an upper part with indeterminacy $I_N \in [I_L, I_U]$. Moreover for intervals, the lower value of the indeterminacy interval is always taken as zero under classical statistics extension i.e. $I_L = 0$. But the upper value of indeterminacy interval can be found by $I_U = [(X_{iU} - X_{iL})/X_{iU}]$. In this the indeterminacy interval with respect to each is as $I_N \in [0, (X_{iU} - X_{iL})/X_{iU}]$. Similarly, the neutrosophic mean interval $\bar{X}_N \in [\bar{X}_L, \bar{X}_U]$ is defined as follows:

$$\bar{X}_N = \bar{X}_L - \bar{X}_U I_N; \ I_N \in [I_L, I_U] \tag{2}$$

Where $\bar{X}_L = \sum_{i=1}^{nU} \left(\frac{X_{iL}}{n_L}\right)$ is the lower value of the neutrosophic mean and $\bar{X}_U = \sum_{i=1}^{nU} \left(\frac{X_{iU}}{n_U}\right)$ is the highest value of the neutrosophic means with the indeterminacy interval $I_N \in [I_L, I_U]$. By using the above neutrosophic statistics definition, the variation for resistance (R) interval $[R_L, R_U]$ and for capacitance (C) interval $[C_L, C_U]$:

$$R_N = R_L + R_U I_N; \ I_N \in [I_L, I_U] \tag{3}$$
$$C_N = C_L + C_U I_N; \ I_N \in [I_L, I_U] \tag{4}$$

2.2 Development of Indeterministic Relationship between Capacitance and Resistance:

In the process of establishing the indeterministic relationship between capacitance and resistance, our initial step involves the classical relationship existing between capacitance and resistance within an LCR meter framework. Given the prevalent nature of AC circuits in LCR meter applications, it becomes possible to express the impedance pertaining to a supercapacitor concerning its capacitance as follows:

$$Z = \frac{1}{2j\pi fC} \tag{5}$$

The frequency 'f' can be written as $f = \frac{\omega}{2\pi}$, so the equation (5) becomes:

$$Z = \frac{1}{j\omega C} \tag{6}$$

Here 'j' is a complex no having value '$\sqrt{-1}$' so we ignore it. Also if we consider that resistance and impedance are equal for LCR meter the above equation can be written as:

$$R = \frac{1}{\omega C} \tag{7}$$

This is a deterministic/classical relationship between resistance and capacitance. It is seen that both have inverse relation, i.e. as the capacitance of a supercapacitor increases the resistance starts to decrease. So, the indeterministic relationship by using the definition of neutrosophic statistics can be written as:

$$R = \frac{1}{\omega * (C_L + C_U I_N; I_N \epsilon [I_L, I_U])} \tag{8}$$

And

$$C = \frac{1}{\omega * (R_L + R_U I_N; I_N \epsilon [I_L, I_U])} \tag{9}$$

The Eq. (8) will be used if someone wants to calculate the resistance when he has measured capacitance in interval from LCR for a supercapacitor. Similarly, the Eq. (9) will be used if someone wants to calculate the capacitance when he has measured resistance in interval.

3. Data Collection

In this scenario, we employ a capacitor for which the resistance is subjected to measurement through employment of an LCR meter. The measurement is conducted concerning alterations in the current at a frequency of 1 kHz, while maintaining a constant input of 1.0 V. The process involves determining the resistance in intervals, wherein at specific current levels, both the maximum and minimum variations in resistance are meticulously recorded. This is visually represented in Figure 1, showcasing the observed range of resistance as [minimum resistance, maximum resistance].
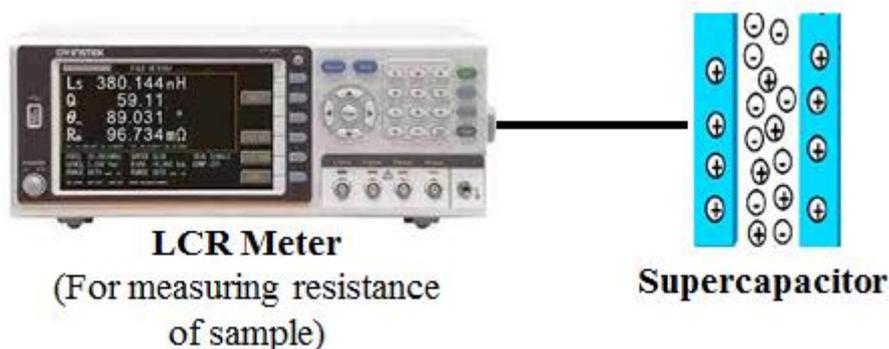

Figure 1. Characterization setup.

In our investigation, it is pertinent to clarify that no experimental procedures were conducted by our team. Instead, we acquired the relevant resistance data from a published paper, specifically by extracting the data points from its graphical representation [21]. Subsequently, we employed the

aforementioned indeterministic formula to derive the corresponding capacitance values in conjunction with the collected resistance data, carefully analyzed within specific intervals. In our analytical pursuit, we applied both classical and neutrosophic methodologies to comprehensively analyze the dataset encompassing resistance and capacitance values. These methodologies allowed us to gain valuable insights and draw meaningful conclusions from the gathered information.

4.   Results and Discussion

The collected resistance data (by reading the graph of Figure 2 (b) from [10]) of the supercapacitor with respect to change in current as shown in Table 1.

Table 1. Data of resistance of supercapacitor with respect to current.

Current	Resistance
(A)	(Ω)
0.1	[30.18, 40.92]
0.2	[18.54, 26.67]
0.3	[12.86, 18.34]
0.4	[10.01, 13.19]
0.5	[7.10, 9.21]
0.6	[7.01, 7.64]
0.7	[5.90, 6.17]
0.8	[5.25, 5.29]

Now, let we use the above indeterministic relation to calculate the capacitance from the above resistance data of supercapacitor. For example we calculate the capacitance for interval of resistance [30.18, 40.92] with respect to 0.1 A current at 1 kHz = 1000 Hz. From the Eq. (9), $'R_L' = 30.18$, $'R_U' = 40.92$, $'I_L' = 0$ (according to the definition of neutrosophic statistics) and $'I_U' = 0.26$ (according to the definition of neutrosophic statistics) so the capacitance can be written as:

$$C = \frac{1}{(1000)*(30.18 + 40.92 I_N; I_N \epsilon [0,0.26])} \tag{10}$$

If we choose the '0.02' interval difference for indeterminacy interval, we get the calculated values of the capacitance showing in the Table 2 for single interval i.e. [30.18, 40.92] from the above equation:

Table 2. Calculated value of capacitance and resistance values by indeterminacy relationship.

Indeterminacy Variation [0, 0.26]	Resistance [30.18, 40.92] (Ω)	Capacitance (F)
0	30.18	0.033135
0.02	30.9984	0.03226
0.04	31.8168	0.03143
0.06	32.6352	0.030642
0.08	33.4536	0.029892
0.10	34.272	0.029178
0.12	35.0904	0.028498
0.14	35.9088	0.027848
0.16	36.7272	0.027228

0.18	37.5456	0.026634
0.20	38.364	0.026066
0.22	39.1824	0.025522
0.24	40.0008	0.025
0.26	40.9232	0.024498

The Table 2 is expressing the calculated values of capacitance for a single interval of the resistance. The capacitance values are calculated from the equation (10) and resistance values are calculated from the equation (3). Now, we plot the graph between the capacitance vs resistance as shown in Figure 2.
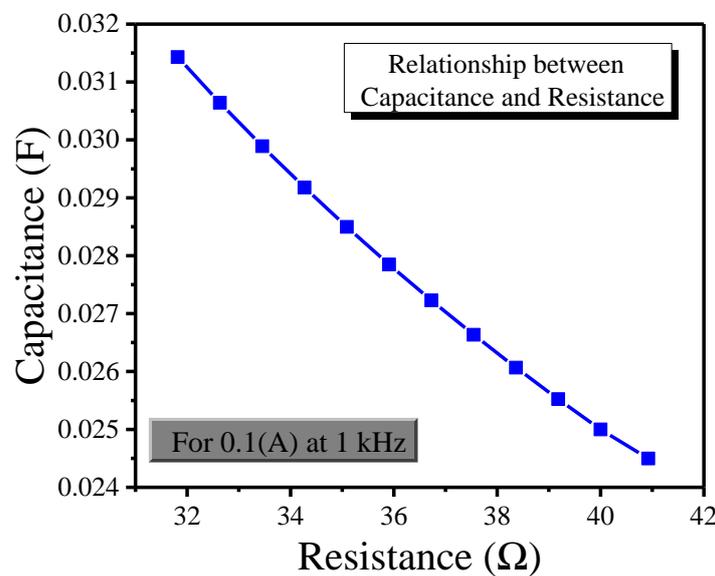

Figure 2. Relationship of capacitance and resistance for 0.1 (A) current at 1 kHz.

The Figure 2 is expressing the relationship between capacitance and resistance for the first interval of resistance i.e. [30.18, 40.92]. It is seen that the resistance and capacitance values calculated from the interval satisfy the relationship for LCR meter as expressed in equation (7) i.e. with increased in resistance capacitance decreased. In the same way, we can calculate the value of capacitance for each interval of table 1. And can also draw the graph for each interval.

4.1 Computational Approach for Indeterministic Relationship

Now we use the computational approach for calculating the values from the above indeterministic relationship. So the algorithm to run the above relation/formula on computer as following:

Step 1:   Start program

Step 2:   Run a loop from $I_N = I_L \text{ to } I_N = I_U$ (For given interval)

Step 3:   Execute formulas:

$$C = \frac{1}{(1000)*(30.18 + 40.92 I_N)} \text{ (For calculating the variance value of capacitance)}$$

$$R = R_L + R_U I_N \text{ (For analyzing the variance value of resistance)}$$

Step 4:   Collect data in table and draw graph

Step 5:   Increment of 0.02 and go to step 3

Step 6:   End loop

Step 7:   End program

The above algorithm will be used to run the indeterministic relationship on any computer program.

4.2 Advantages of Indeterministic Relationship

- Utilizing the aforementioned indeterministic relation, it becomes feasible to directly input the values as interval values without necessitating any additional adjustments within the interval. Consequently, this enables a straightforward computation of both resistance and capacitance.Through the utilization of a singular interval, it is possible to construct a comprehensive graph that facilitates the analysis of capacitance and resistance for various devices, such as sensors and capacitors, among others.
- These formulas exhibit high computational efficiency and can be effortlessly applied using any standard computer software, thereby streamlining the analysis process.
- Employing this approach allows for a more precise examination of data variance, leading to the acquisition of more insightful and valuable information from the dataset.

4.3 Limitation of Indeterministic Relationship

- The aforementioned indeterministic relationship is specifically designed for the purpose of analyzing resistance or capacitance data obtained from LCR meter measurements.
- To apply this relationship effectively, it is imperative that the dataset of capacitance and resistance comprises interval values. The validity and applicability of the relationship rely on the availability of such interval data in the dataset.

4.4 Analysis of data

We now proceed to perform a comprehensive analysis of the entire dataset, employing the neutrosophic method. Furthermore, we aim to make a comparative assessment between the outcomes obtained from the neutrosophic analysis and the previously utilized classical method of graph representation.

To initiate this comparative study, we have utilized the resistance data presented in Table 1. Employing the neutrosophic analysis technique, we examine the data and draw relevant conclusions. Subsequently, we contrast the results with those derived through the classical method of graph plotting. The findings from both the classical and neutrosophic analyses are tabulated in Table 3. It is important to emphasize that, for this phase of analysis; we have exclusively utilized the resistance data available in the dataset.

Table 3. Classical and neutrosophic analysis of resistance interval data.

Current (A)	Classical Method	Neutrosophic Method
0.1	35.74 ± 5.18	$30.18 + 40.92 I_N; I_N \in [0, 0.26]$
0.2	21.12 ± 5.55	$18.54 + 26.6 I_N;\ I_N \in [0, 0.31]$
0.3	15.92 ± 2.42	$12.86 + 18.34 I_N; I_N \in [0, 0.30]$
0.4	11.59 ± 1.6	$10.01 + 13.19 I_N; I_N \in [0, 0.24]$
0.5	8.01 ± 1.2	$7.10 + 9.21 I_N; I_N \in [0, 0.23]$
0.6	7.32 ± 0.32	$7.01 + 7.64 I_N; I_N \in [0, 0.08]$
0.7	6.06 ± 0.11	$5.90 + 6.17 I_N; I_N \in [0, 0.04]$
0.8	5.27 ± 0.02	$5.25 + 5.29 I_N; I_N \in [0, 0.01]$

Based on the findings presented in Table 3, it becomes evident that the classical analysis of resistance data was executed using the classical mean/average formula. However, it is notable that the classical method only yields a single value, accompanied by an associated error, at a specific data point. For instance, at a current of 0.1A, the resistance value derived through the classical approach is 35.74 ± 5.18. It is evident that the concept of intervals, which represents the indeterminacy, is lost within the classical analysis. Consequently, we do not recommend the classical method for analyzing interval data of resistance due to its limited reliability in decision-making and its lack of flexibility in problem resolution.

This limitation necessitates a shift toward the neutrosophic method for interval data analysis. The neutrosophic method provides an equation for each data interval, along with its corresponding indeterminate interval. As observed, the neutrosophic analysis proves to be more reliable since it effectively addresses indeterminacy and furnishes comprehensive information concerning the variance of resistance changes at specific current levels. For instance, at 0.1A current, the neutrosophic analysis provides an equation of the form $R = 30.18 + 40.92\,I_N$, where $I_N \epsilon\,[0, 0.26]$, with an indeterminate interval of [0, 0.26]. According to the neutrosophic analysis, the resistance value lies within the range of 30.18 and 40.92 by incorporating different indeterminacy values ranging from 0 to 0.26.

To better illustrate these distinct analytical approaches, we have depicted the classical and neutrosophic graphs in Figure 3, providing a visual representation of their respective outcomes.
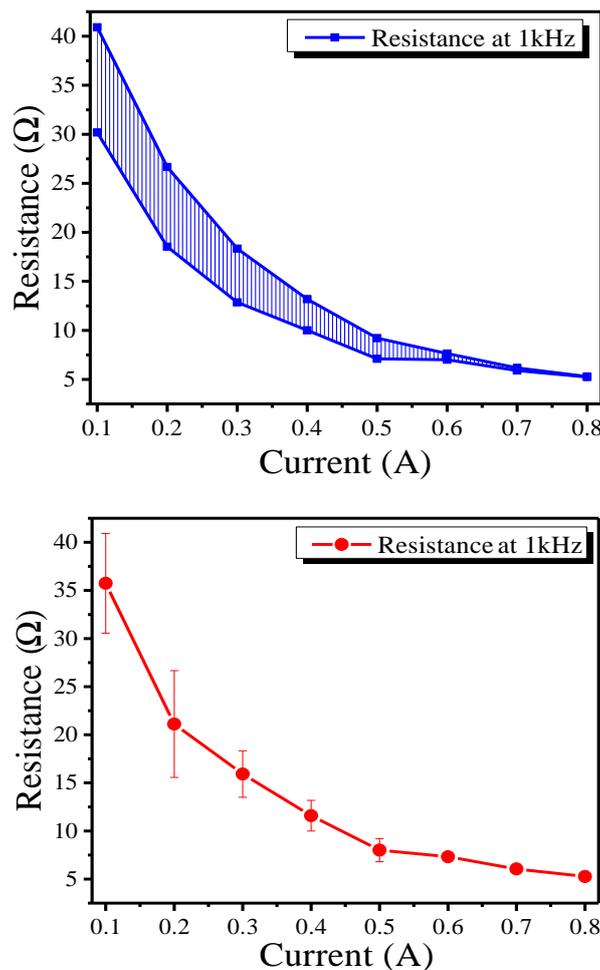

Figure 3. Left side is neutrosophic graph and right side is classical graph.

The plots displayed in Figure 3 facilitate a comprehensive comparison between the classical and neutrosophic graphs. The classical graph, while commonly employed, demonstrates limited flexibility and information conveyance when elucidating the resistance characteristics of a supercapacitor. It primarily adheres to fixed-point values or represents data points solely at specific fixed values. On the contrary, the neutrosophic graph exhibits a remarkable degree of flexibility, rendering it capable of providing valuable and decision-relevant information. The ability to work with interval data values allows for more informed conclusions to be drawn.

In our visual representation of the classical analysis, we have utilized error bars, as commonly seen in the works of other researchers. However, it is essential to acknowledge that error bars, while widely used, are not statistically effective in showcasing data variance. Instead, they depict the error found in data, which may result from personal error, sample handling, or mechanical discrepancies. This distinction is critical, as error bars do not effectively represent the variation present within the data.

Conversely, the neutrosophic method emerges as a highly valuable and effective approach for interval data analysis, as it requires no manipulation or modification of intervals. By directly utilizing the interval data, this method offers a comprehensive understanding of the variance in the supercapacitor's resistance measured through the LCR meter in response to current fluctuations. In light of its superior performance in dealing with interval data, we have opted for the neutrosophic approach to conduct our analysis, enabling us to gain meaningful insights into the behavior of the supercapacitor under study.

5.   Conclusions

The present study represents an application of modern material statistics, specifically leveraging the principles of neutrosophic statistics. In this work, we introduce an innovative indeterministic relationship for interval values of capacitance and resistance, both of which are measured using an LCR meter for a supercapacitor. The primary objective of this relationship is to facilitate the calculation of capacitance or resistance values directly from their corresponding interval values, without necessitating any alteration or adjustment to the intervals and their associated indeterminacy. To demonstrate the efficacy of the proposed indeterministic relationship, we have included a practical example, showcasing how capacitance values can be calculated from the interval data of resistance for a supercapacitor. Through this example, we illustrate the ease and accuracy with which this relationship can be applied to real-world scenarios. Furthermore, to comprehensively understand the analysis methodologies of both neutrosophic and classical statistics, we have incorporated an additional example and compared the output tables and graphs derived from each approach. The findings from this comparative analysis allowed us to draw conclusive insights. As a result of our investigations, we have arrived at the noteworthy conclusion that the proposed neutrosophic statistical method proves to be more effective and informative in analyzing interval data collected from an LCR meter. The ability to work directly with interval values without losing indeterminacy enhances the reliability and utility of the neutrosophic approach, underscoring its significance in modern material statistics and its potential for practical applications in various research domains.

Data availability
The datasets generated during and/or analyzed during the current study are not publicly available due to the privacy-preserving nature of the data but are available from the corresponding author upon reasonable request.
Conflict of interest
The authors declare that there is no conflict of interest in the research.
Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Péan, C., et al., Multi-scale modelling of supercapacitors: From molecular simulations to a transmission line model. Journal of Power Sources, 2016. 326: p. 680-685.
2. Rafik, F., et al., Frequency, thermal and voltage supercapacitor characterization and modeling. Journal of power sources, 2007. 165(2): p. 928-934.
3. Faranda, R., A new parameters identification procedure for simplified double layer capacitor two-branch model. Electric Power Systems Research, 2010. 80(4): p. 363-371.
4. Gualous, H., et al., Experimental study of supercapacitor serial resistance and capacitance variations with temperature. Journal of power sources, 2003. 123(1): p. 86-93.
5. Lämmel, C., et al., Investigations of electrochemical double layer capacitor (EDLC) materials–a comparison of test methods. Materialwissenschaft und Werkstofftechnik, 2013. 44(7): p. 641-649.
6. Navalpotro, P., et al., Insights into the energy storage mechanism of hybrid supercapacitors with redox electrolytes by Electrochemical Impedance Spectroscopy. Electrochimica Acta, 2018. 263: p. 110-117.
7. Licht, F., M. Davis, and H. Andreas, Charge redistribution and electrode history impact galvanostatic charging/discharging and associated figures of merit. Journal of Power Sources, 2020. 446: p. 227354.
8. Ramakrishnan, M.J. and P. Vaidya, Digital Meter for measuring Capacitance of an Ultra Capacitor.
9. Samukaite-Bubniene, U., et al., Towards supercapacitors: Cyclic voltammetry and fast Fourier transform electrochemical impedance spectroscopy based evaluation of polypyrrole electrochemically deposited on the pencil graphite electrode. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2021. 610: p. 125750.
10. Helseth, L.E., Comparison of methods for finding the capacitance of a supercapacitor. Journal of Energy Storage, 2021. 35: p. 102304.
11. Afzal, U., et al., Neutrosophic statistical analysis of resistance depending on the temperature variance of conducting material. Scientific reports, 2021. 11(1): p. 1-6.
12. Afzal, U., et al., Fabrication of a surface type humidity sensor based on methyl green thin film, with the analysis of capacitance and resistance through neutrosophic statistics. RSC Advances, 2021. 11(61): p. 38674-38682.
13. Simić, M. Realization of digital LCR meter. in 2014 International Conference and Exposition on Electrical and Power Engineering (EPE). 2014. IEEE.
14. Nara, A., et al., Applicability limits of the two-frequency capacitance measurement technique for the thickness extraction of ultrathin gate oxide. IEEE transactions on semiconductor manufacturing, 2002. 15(2): p. 209-213.
15. Lallart, M., S. Pruvost, and D. Guyomar, Electrostatic energy harvesting enhancement using variable equivalent permittivity. Physics Letters A, 2011. 375(45): p. 3921-3924.
16. Ye, J., Improved cosine similarity measures of simplified neutrosophic sets for medical diagnoses. Artificial intelligence in medicine, 2015. 63(3): p. 171-179.
17. Christianto, V., R.N. Boyd, and F. Smarandache, Three possible applications of neutrosophic logic in fundamental and applied sciences. 2020: Infinite Study.
18. Aslam, M., Enhanced statistical tests under indeterminacy with application to earth speed data. Earth Science Informatics, 2021: p. 1-7.
19. Afzal, U., M. Aslam, and A.H. Al-Marshadi, Analyzing imprecise graphene foam resistance data. Materials Research Express, 2022.
20. Afzal, U., et al., Neutrosophic statistical analysis of resistance depending on the temperature variance of conducting material. Scientific Reports, 2021. 11(1): p. 23939.
21. Afzal, U., et al., Fabrication and characterization of a highly sensitive and flexible tactile sensor based on indium zinc oxide (IZO) with imprecise data analysis. ACS omega, 2022. 7(36): p. 32569-32576.