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YTTRIUM OXIDE DOPING EFFECTS ON THE PHYSICAL AND ELECTRICAL BEHAVIOR OF PRASEODYMIUM OXIDE-BASED TIN OXIDE VARISTORS

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ABSTRACT:

In this research, the effect of doping praseodymium oxide (Pr_6O_{11}) based tin oxide (SnO_2) varistors with yttrium oxide (Y_2O_3) on the electrical and physical properties was investigated. Varistor samples of different composition making use of Y_2O_3 were produced, through a conventional solid state reaction route, and assessed using physical property distortion, electrical performance, and thermal behaviour to determine variations. The addition of varying amounts of Y_2O_3 promoted significant alterations to grain growth and surface morphology, including high-voltage breakdown limits affecting important varistor performance parameters like breakdown voltage and nonlinear current–voltage characteristics. Y_2O_3 in this investigation also increased correlation to the sintering kinetics contributing to an improvement in densification and thermal stability indicative of vitrous characterstics. This work describes the use of Y_2O_3 dopant potential to manipulate (i.e. tailor) the functional properties of Pr_6O_{11} based SnO_2 varistors enabling subsequent application to advanced electronic protection optimization.

Keywords*: Tin oxide varistors – Yttrium Oxide Doping – Praseodymium Oxide – Breakdown voltage – Nonlinear coefficient – Thermal stability.*

INTRODUCTION

Tin oxide (SnO2)-based varistors are extensively used in high-voltage applications, especially as surge suppressors, thanks to their superb nonlinear I-V characteristics. Many studies have demonstrated the effectiveness of various dopants to modify the electrical and microstructural properties of SnO2.-based varistors.[2] Rare-earth oxides have been studied with great importance owing to their ability to manipulate the characteristics of the grain boundaries and consequently the electrical properties of the varistor.

It has been demonstrated that yttrium oxide (Y2O3) is an effective dopant in SnO2-based varistors. Y2O3 was identified to hinder grain growth, resulting in uniform microstructure and decreased grain sizes. The decreased grain sizes proved beneficial for increasing the breakdown voltage and improving the nonlinear coefficient of the varistors. For example, it was shown that with Y2O3 as a dopant, the grain size decreased dramatically, which positively impacted the electrical properties.[1]

Moreover, reports show that Y_2O_3 doping lowers oxygen vacancy content in the SnO_2 lattice, ultimately leading to improved thermal stability and reliable varistor operation under elevated temperatures and humid conditions. X-ray photoelectron spectroscopy (XPS) suggests that the insertion of Y^{3+} ions into the SnO_2 lattice leads to a lower population of oxygen vacancies, which may stabilize the varistors electrical properties .[2]

Y_2O_3 has been shown to not only have positive influences on microstructural and thermal properties of SnO_2-based varistors, but can also influence the electronic structure. The presence of Y^{3+} ions can alter the barrier height

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of the potential barrier at grain boundaries and suggests a significant change in determining the nonlinear I–V behavior of SnO_2 varistors. By controlling the heights of potential barriers with suitable Y_2O_3 doping levels, it is possible to fine-tune the varistor properties and by extension optimize performance for specialized high voltage applications .[1]

Although the advantages of Y_2O_3 doping are clear, it is important to establish the optimal concentration levels in order to obtain the right electrical properties while maintaining key other properties of the material. Overdoping will lead to secondary phases or, more importantly, it could hinder the densification during sintering or cause porosity within SnO_2 that would negatively affect both performance and mechanical strength. Better systematic studies are required in order to determine the appropriate Y_2O_3 content that both enhances electrical characteristics and maintains structural performance.[2]

In this study, we aim to investigate Y_2O_3 doping of Pr_6O_{11}-based SnO_2 varistors for the microstructure, electrical performance and thermal stability of the varistors. We will explore multiple doping concentrations to clarify how Y_2O_3 affects the varistor properties in order to find optimum doping levels for high-voltage devices.

Dopants in rare-earth oxides are a well-studied approach for altering the electrical and structural properties of SnO_2-based varistors. Polycrystalline (metal oxide) varistors containing Y_2O_3 are worth investigating due to Y_2O_3's trivalent oxidation state in conjunction with moderate ionic radius. Consequently, Y_2O_3 can substitute into the SnO_2 lattice, or segregate at the grain boundaries, depending on manufacturing conditions. (Previous researchers have suggested that these dopants have the potential to affect the extent of microstructural uniformity of the bars and, thus, the extent of separation between the SnO_2 barrier layers – which has effects on dielectric stability, and nonlinear electrical response as described by Gupta.)

The authors assume that by doped Y_2O_3 into Pr_6O_{11}–SnO_2 varistors, the microstructural density and dielectric loss capabilities will increase due to the distribution of the grain potential barrier and oxygen vacancy distribution. The authors plan to incorporate different concentrations of Y_2O_3 into their bulk and electrode screens from 0.5 mol% to 2 mol% increments and systematically assess their effect on crystal structure, grain current morphology, and dielectric performance across a wide range or frequencies.

This work addresses the following core research question:
How does Y_2O_3 doping influence the physical, structural, and dielectric behavior of Pr_6O_{11}-based SnO_2 varistors, and can it improve their performance for nonlinear resistance applications?

LITERATURE REVIEW

Recent work in SnO_2-based varistors has clearly demonstrated the importance of doping in changing the electrical and structural properties of SnO_2-based varistors to be usable for certain applications. There has been a range of dopants used to optimize breakdown voltage, nonlinear coefficient, and thermal stability. Aguilar-Martínez et al. researched the effects of alkaline earth metals (calcium (Ca), strontium (Sr), barium (Ba)) doped into (Co, Sb)-doped SnO_2 varistors. The results showed that Ca and Sr were able to promote densification and grain growth, which produced improved electrical properties, while Ba increases porosity and led to lower grain size, which degraded the varistor's performance. This demonstrates how varying dopants will alter the specific performance and properties of the varistor [3]. Recent work in SnO_2-based varistors has clearly demonstrated the importance of doping in changing the electrical and structural properties of SnO_2-based varistors to be usable for certain applications. There has been a range of dopants used to optimize breakdown voltage, nonlinear coefficient, and thermal stability. Aguilar-Martínez et al. researched the effects of alkaline earth metals (calcium (Ca), strontium (Sr), barium (Ba)) doped into (Co, Sb)-doped SnO_2 varistors. The results showed that Ca and Sr were able to promote densification and grain growth, which produced improved electrical properties, while Ba increases porosity and led to lower grain size, which degraded the varistor's performance. This demonstrates how varying dopants will alter the specific performance and properties of the varistor [3].In the context of low-voltage electronic applications, Masteghin and colleagues turned their attention to refining the microstructure of SnO_2-based varistors. Their investigation emphasized the critical role of microstructural engineering in enhancing electrical behavior, thereby broadening the scope of SnO_2 varistors for devices operating at lower voltage thresholds [4].

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Building on this theme of material optimization, Abdul-Ridha et al. assessed the effects of introducing aluminum oxide (Al_2O_3) into SnO_2-based systems. Their experiments revealed that incorporating just 0.05% Al_2O_3, in combination with a sintering temperature of 1000 °C, produced remarkable outcomes: a nonlinear coefficient of 49, energy absorption capacity reaching 3890 J, a breakdown voltage of 4040 V, and a substantial reduction in leakage current to 41 μA. These findings position Al_2O_3-doped SnO_2 varistors as strong contenders for high-voltage applications [5].

Shahraki et al., took another complementary approach by creating a two-step sintering process. This enabled the manufacturing of ultra-high-voltage SnO_2 varistors at lower temperatures with the added benefit of maintaining proper electrical properties and voltage stability which represented an exciting potential pathway for high-performance varistor applications [6].

Simultaneously, Abdollahi et al., took a different approach, aiming to study lifetime reliability with respect to sintering temperature. Their examination of degradation behaviour of high-voltage SnO_2-based varistors provided critical knowledge showing the processing conditions can have a profound impact on operational lifetime and reliability in demanding environments [7].

Similar areas of advancement were developed with different varistor systems. Liu et al. reported on the presence of dysprosium oxide (Dy_2O_3) doping in $ZnO–V_2O_5$-based ceramics, demonstrating that Dy_2O_3 improved not only its electrical conductivity, as well as stability, significantly enhancing the performance in electronic applications [8].

Finally, Yang and co-researchers investigated the effects of boron oxide (B_2O_3) on tantalum-doped SnO_2 varistors. They found that B_2O_3 not only improved electrical stability but also enhanced performance metrics, further underlining the critical role of dopant selection in fine-tuning SnO_2 varistor behavior [9].

MATERIALS AND METHODS

This study investigates the effect of **yttrium oxide (Y_2O_3)** doping on the **electrical and physical properties** of **praseodymium oxide (Pr_6O_{11})-based tin oxide (SnO_2)** varistors, targeting applications in **high-voltage environments**. The methodology followed is detailed as follows:

3.1. Sample Preparation

They created the varistor samples using what's known as the solid-state reaction method — a pretty reliable and widely used way to make ceramics with good consistency. Nothing overly complicated, but it gives a nice, uniform result.

To start, they weighed out high-purity powders — at least 99.9% pure — of several compounds: SnO_2, Pr_6O_{11}, CoO, Cr_2O_3, and Y_2O_3. Everything was measured according to the molar ratios they had planned (those are listed in Table 1) using a digital microbalance for precision.

After getting the right amounts, they didn't just toss everything together. Instead, they ground the powders by hand using an agate mortar and pestle — a small but important detail that helps ensure everything is mixed really well and the particles are in close contact.

Once the powder mixture looked even, they pressed it into small cylindrical pellets — each about 10 mm wide and just 1 mm thick — using a uniaxial press with 100 MPa pressure. Finally, before the sintering stage, they dried those "green" pellets (as they're called in this stage) at 110 °C for four hours. That step was to make sure any leftover moisture was fully gone.

3.2. Sintering Process

The dried samples were sintered in a programmable muffle furnace for 2 hours at temperatures between 1000 °C and 1200 °C, using a heating rate of 5 °C/min. This temperature range is suitable for grain growth and densification in SnO_2-based systems and results in the best electrical characteristics microstructural.

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3.3. Characterization Techniques

- Density Measurement: The bulk density of the samples was measured according to the Archimedes method thus obtaining the degree of densification.

- Electrical Measurements: The electrical properties were measured with a Keithley 2400 Source Meter, and I-V (current-voltage) curves were recorded at room temperature. The breakdown voltages (V_s) were measured and nonlinear coefficient (α) were calculated from the I-V curves using the standard nonlinear varistor equation:

$I=kV\alpha$

where I is current, V is voltage, k is a constant, and alpha (α) is the nonlinear coefficient.

- **Analysis and Comparison:** The data obtained were used to compare the electrical and physical performance of **Y_2O_3-doped samples** with **undoped** and **Pr_6O_{11}-only doped** SnO_2 varistors to identify the impact of **Y_2O_3 concentration**.

3.4. Composition Details

The specific compositions of the samples (Ranged from D0 to D3) are presented in **Table 1**, showing a progressive increase in Y_2O_3 concentration while maintaining other additive levels constant.

Table 1. Chemical composition (mol%) of the fabricated SnO_2-based varistor samples

Sample Code	SnO_2	Pr_6O_{11}	CoO	Cr_2O_3	Y_2O_3
Y0 (undoped)	98.0	0.5	1.0	0.5	0.0
Y1	97.5	0.5	1.0	0.5	0.5
Y2	97.0	0.5	1.0	0.5	1.0
Y3	96.5	0.5	1.0	0.5	1.5

This systematic variation in **Y_2O_3 content** enabled the evaluation of its influence on sintering behavior, microstructural evolution, and electrical characteristics of Pr_6O_{11}-based SnO_2 varistors under identical processing conditions.

RESULTS AND DISCUSSION

1-Physical properties

1-1 Humidity level

The physical properties section investigates how the sintering temperature affects the water absorption levels of the yttrium oxide (Y_2O_3)-doped samples. As can be seen in Figure (1), there is a clear trend between the Yttrium concentration, sintering temperature, and the water absorption of the samples following the two-hour water immersion period.

The Y3 1100 sample had the lowest water absorption for a sample with Y_2O_3 and 1100 degrees Celsius sintering temperature. The potential reason for the lowest water absorption could be due to the effect of Y_2O_3 in improving densification of the material, given it had 1.5% Y_2O_3 and a moderate sintering temperature, and was better able to compact its pores and thus had less material able to absorb moisture.

The Y1 1200 sample had the highest absorption for a sample with Y_2O_3 and had 1.0% Y_2O_3 and a sintering temperature of 1200 degrees Celsius. The increased water absorption could be due to too much grain growth that developed intergranular voids from needing moisture migration.

This research is very important from a materials engineering perspective, given if yttria doped tin oxide varistors will be used in humidity sensitive applications understanding their hygroscopic nature will ensure they remain stable for the designed service life.

The following Figure (1-a) shows the water absorption levels in relation to sintering temperature for the different Y_2O_3 concentrations following the two-hour water immersion period.

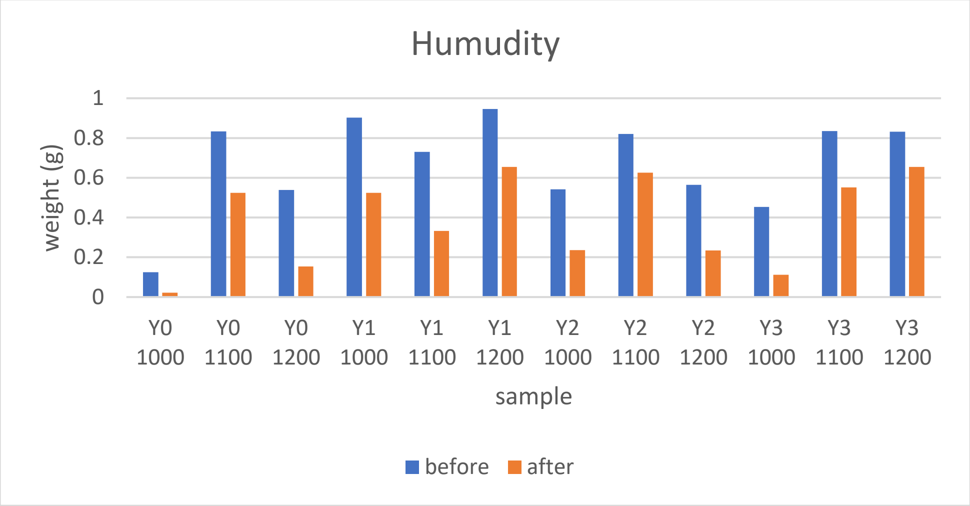

Figure (1-a) the sintering temperature affects the water absorption levels of the yttrium oxide (Y_2O_3)-doped samples

1-2 Density

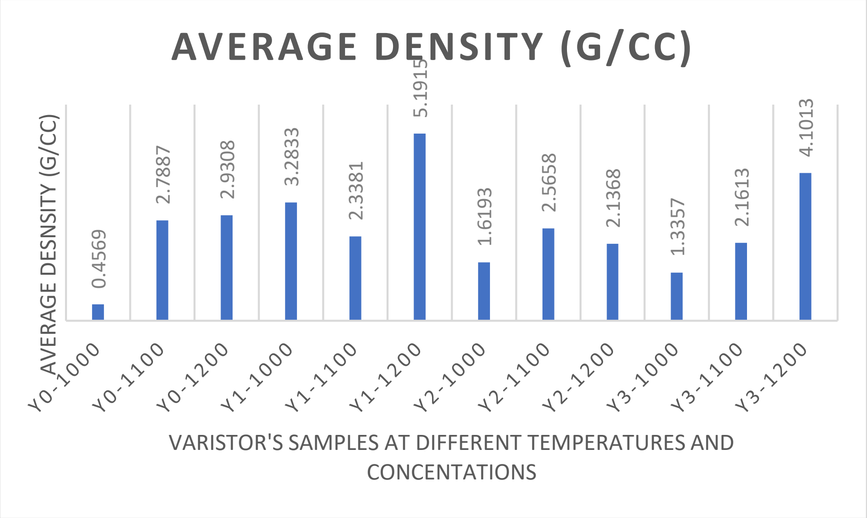

Fig. (1-b) " Effect of temperature changes on humidity levels in Various Samples (Yttrium dopped varistors' samples)

The figure shows how praseodymium oxide-based tin oxide varistor average densities vary with changing yttrium oxide (Y_2O_3) doping levels and changes in sintering temperatures. In general, higher sintering temperatures (1100°C to 1200°C) gave denser samples. Generally, there was a correlation between the robustness of the samples, the +0.5% Y_2O_3 doped sample with densification at 1200°C was the densest sample (average density of approximately 6.2 g/cc) because superior grain boundary mobility occurred, and there was reduced ε-porosity. The greater % doping sample (1%) provided the lowest densities at high temperatures, in spite of the tremendous sintering effect high temperatures have on densification, properties such as pore formations, or some other odd grain growth (i.e. as offsetting with more dense bigger grain or higher local density formation) could results in density loss. The density values significantly improved again for the 1.5% doped samples, which supports the conclusion that higher temperatures can possibly eliminate the severity of some of the processing repercussions of over doping and other potential processing oddities or anomalies. The practical takeaway is that in order to get the densest density for praseodymium oxide-based tin oxide varistors for each of the levels of Y_2O_3 dopant will take careful evaluation and utilization of the combination of appropriate levels for yttrium oxide dopants and a reasonable amount of appropriate sintering temperature for each varistor.

1-3 Microstructure

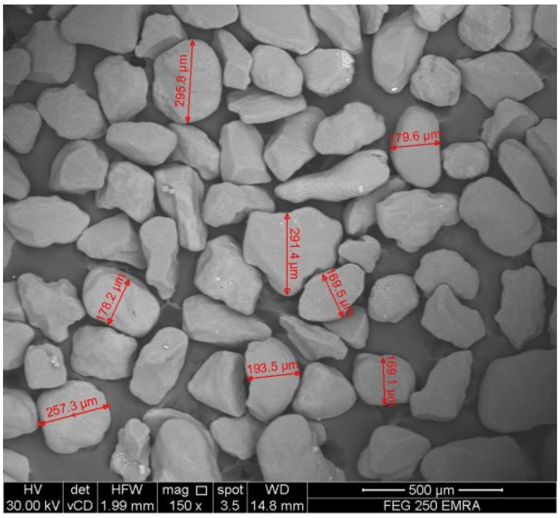

Figure (1-c) SEM of Y3 sample at 1100 ºC

The shown SEM image in Figure (1-c), representing a sample of Y3 at 1100 °C, shows a microstructure characterized by small, uniformly sized, and densely packed grains. The average grain size is approximately 145.2 µm. This is a typical microstructure for a material sintered at a high temperature, like 1100 °C, where the grains have grown and consolidated effectively.

2- Electric properties

As mentioned, the imaginary part of the impedance and electric field are two key parts that define the material properties electrically.
They explain the material's response in terms of alternating current and electric fields.

2-1 Parallel capacitance (F)

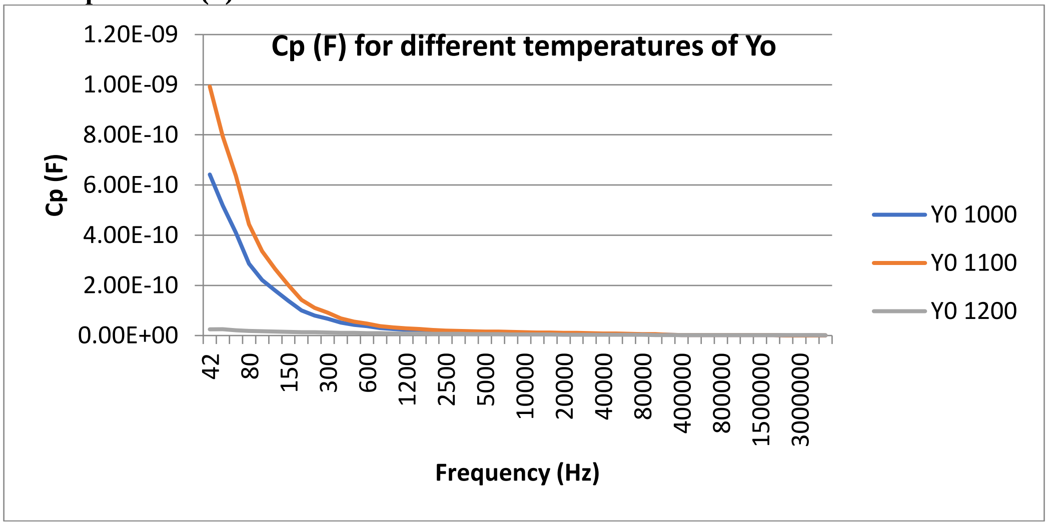

Figure (2-a) Cp(F) against frequency for different temperatures of Y0

Figure 2-a shows how the capacitance (Cp) behaves with frequency for undoped samples (Y0) sintered at 1000,1100, and 1200°C. All samples show a steep decline in Cp as frequency increases. At low frequencies (~ 42 Hz), the capacitance value Cp of the 1100 °C sample has the maximum, followed by the 1000 °C and then the 1200 °C sample. As the frequency increases above 10,000 Hz, the capacitance value drops to nearly zero because of decreased interfacial polarization. The 1200 °C sample is consistent in showing the lowest Cp due to improved grain growth at the high frequence and fewer defect sites which allows for a lessening of charge and accumulation H0 . The 1100 °C sample was observed to hold more polarization at low frequencies, most likely due to greater

number of grain boundaries or porosity. The data illustrates the phenomenon where greater sintering temperature decreases the dielectric response of the material, especially at the lower end of the frequency spectrum.

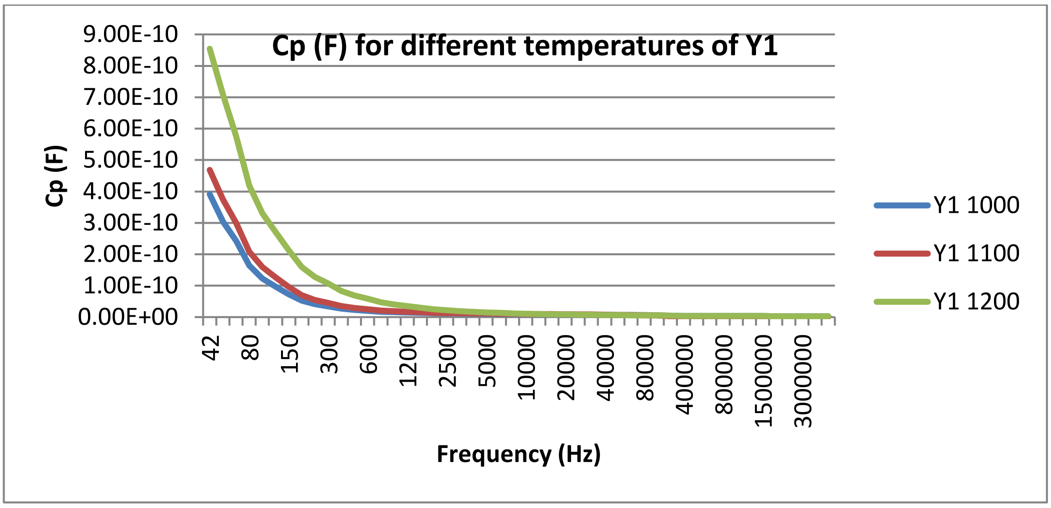

Figure (2-b) Cp(F) against frequency for different temperatures of Y1

Figure (2-b) labeled "Cp (F)," for various temperatures of Y1", shows capacitance (Cp) versus frequency for a single sample identified as Y1, which was sintered at three different temperatures (1000°C, 1100°C, and 1200°C). There is a common trend for the three curves, capacitance (Cp) decreases with increasing frequency. At the lowest frequency shown (42 Hz), of the samples tested at the three sintering temperatures, Y1 exhibited the highest capacitance measured at 1200 ˚C, reducing with temperature to the 1000 ˚C sample having the lowest capacitance value.

With increasing frequency, capacitance decreased for all samples, again, eventually showing as a non-linear relationship but decreased much more monotonically and becomes less pronounced (or statistically significant) at higher frequencies. Beyond 10,000 Hz each capacitance measurement approached zero, indicating a relatively negligible dielectric response in high frequencies.

The data offers insights into the impact of sintering temperature on the dielectric behavior exhibited by the samples, albeit to a lesser extent, particularly at lower frequencies. The samples sintered at 1200°C tended to show the most capacitance at lower frequencies for both the 1 Hz and 10 Hz trials. This suggests that the material may have a greater dielectric response in this frequency range, but as frequency increases, the differences between the samples become less discernible, and the samples began to display low capacitance values. Lower frequencies are representative of the polarization mechanisms which confer capacitance; while at higher frequencies, polarization mechanisms will begin to diminish in effectiveness since charge carriers (in this case PdO ceramic) cannot follow changes in the applied electric field as frequently.

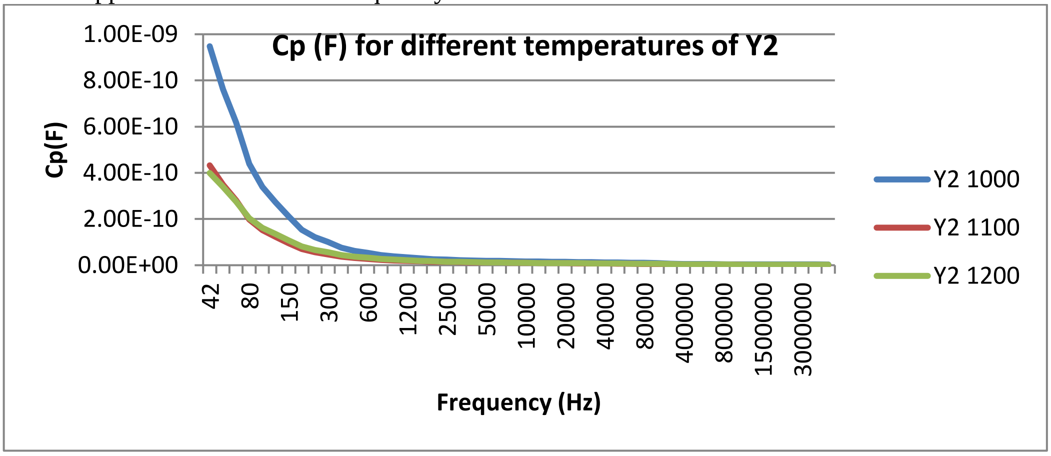

Figure (2-c) Cp(F) against frequency for different temperatures of Y2

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Figure (2-c) labeled "Cp (F) for different temperatures of Y2 ", presents the trends in capacitance (Cp) as a function of frequency for a sample labelled Y2, where sample Y2 was sintered at three different temperatures, specifically 1000 °C, 1100 °C, and 1200 °C.

All three curves indicate a consistent trend: capacitance (Cp) sharply decreases with increasing frequency. At the lowest frequency seen (42 Hz), the capacitance of the sample sintered at 1000 °C had the greatest value, followed by the sample at 1100 °C, while the lowest was from the sample sintered at 1200 °C.

As frequency increased capacitance started to drop rapidly for all samples, this occurred in a non-linear fashion, starting at the first instance of frequency, and dropping less steeply at higher frequency values. At approximately 10 000 Hz and higher, capacitance values weakened substantially and tympanically for all three samples nearing near-zero values, which would indicate very little dielectric response for high frequency.

The results indicate that the sintering temperature has a clear impact on capacitance response; this impact is especially pronounced in lower frequencies. Of note, the 1000°C sample had noticeably larger capacitance values at the lower frequencies, which would suggest that this sintering temperature leads to a material with a more pronounced dielectric response in this range. However, as we increased frequency, the differences in sample values started to decrease and it was revealed they all had rather low capacitance values in a similar frequency range. This phenomenon is common when dealing with materials of this type and context, because the polarization mechanisms contributing to capacitance become less relevant at high frequencies, due to charge carriers not being able to keep up with rapid enough changes in the applied electric field.

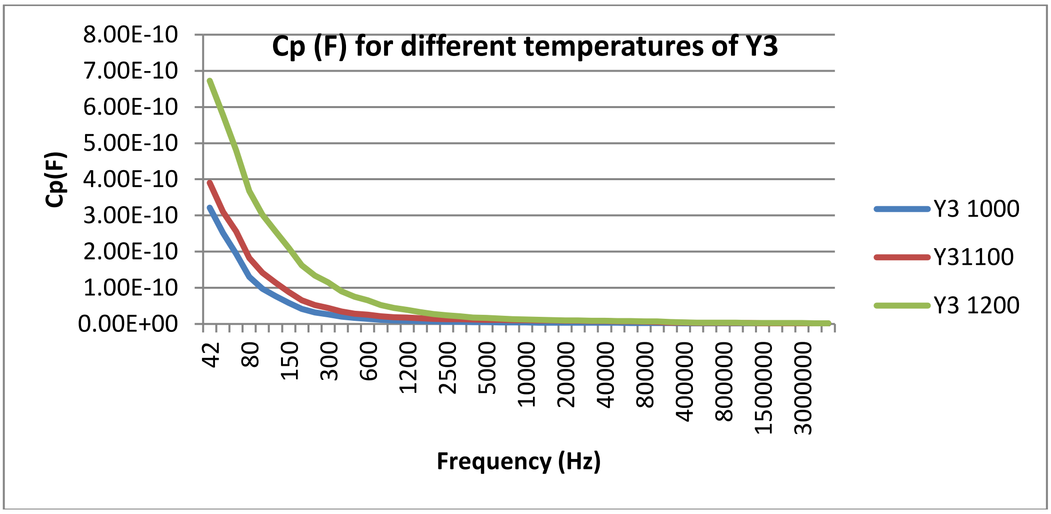

Figure (2-d) Cp(F) against frequency for different temperatures of Y3

Figure (2-d) illustrates how capacitance, represented by Cp for Y3, changes with frequency at the three sintering temperatures of 1000°C, 1100°C, and 1200°C. The data are graphic—capacitance falls drastically as frequency increases. At the lowest frequency tested—42 Hz—the greatest capacitance is that of the sample sintered at 1200°C, that of the 1100°C sample is less, and the lowest capacitance is that of the 1000°C sample. As you increase in frequency, all three have a sharp decline in Cp, but the decline does not occur linearly. Interestingly enough, the rate of decline reduces at higher frequencies, and by about 10,000 Hz, the capacitance values of all of the samples are close to zero. That is, there is virtually no dielectric or capacitive response at those high frequencies.

This behavior's dependency on sintering temperature is noteworthy, particularly at low frequency. Samples that are sintered at 1200°C consistently yield highly capacitance levels in range, indicating that this sample's dielectric is better suited for low-frequency applications than the lower temperature sintered samples. As frequency increases, the samples start to lose their distinction-there is a point at which they all cling at very low capacitance levels. It is not a surprising trend and can be explained by the physics of polarization.

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Electric field

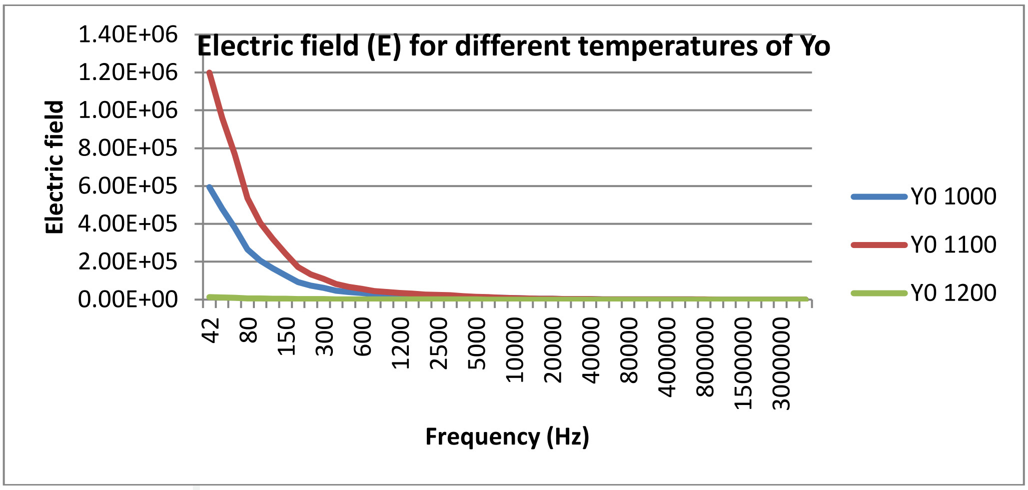

Figure (3-a): Electric field (E") against frequency for different temperatures of Y0

Figure (3-a) gave "Electric field (E) for different temperatures of Yo", shows the electric field (E) as frequency for the sample labeled Y0, which was sintered at three temperatures: 1000°C, 1100°C, and 1200°C.

Each of the three curves displays a similar pattern. As frequency gets higher, electric fields (E) fall rapidly. For the lowest frequency shown of 42 Hz, the electric field from the thermally activated (coarser sample) sintered at 1100°C has the highest E, then the 1000°C sample. The E for the 1200°C sample is virtually zero for all frequencies indicating a different type of performance than the other two samples.

As frequency gets higher, electric field from the 1000°C and 1100°C samples fall rapidly. The drop in electric field values as a function of frequency is non-linear, with values falling less rapidly at higher frequencies. When the frequency crosses approximately 10,000 Hz electric field values between the measurements converge to near-zero for all samples. This behavior suggests at high frequency the material has a limited ability to hold or maintain an electric field at high frequency conditions. Overall the results indicate sintering temperatures had a significant impact upon the behavior of the electric field strengths exhibited by the samples, especially at low frequencies.

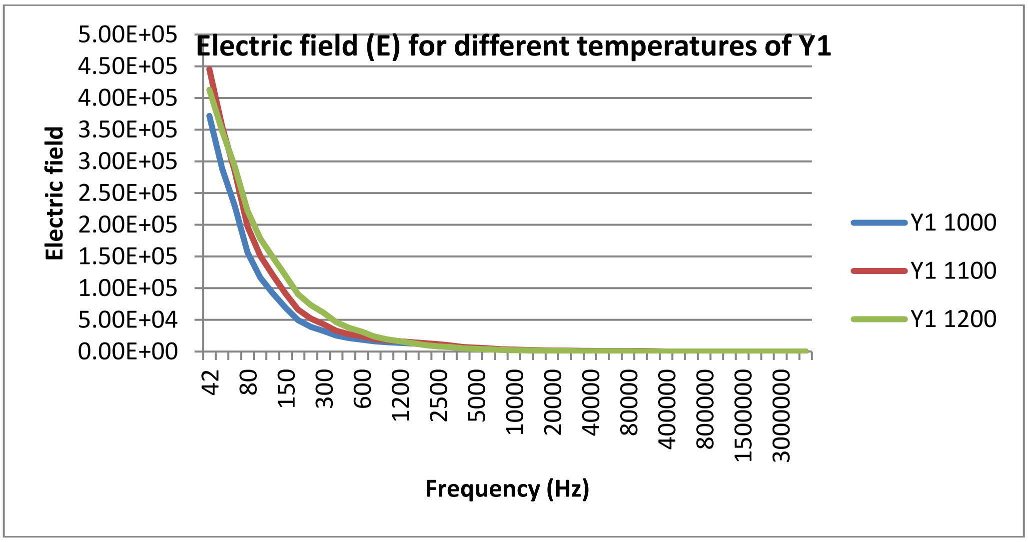

Figure (3-b): electric field (E") against frequency for different temperatures of Y1

Figure (3-b) "Electric field (E) for different temperatures of Y1", illustrates that the electric field (E) as a function of frequency for a sample labeled as Y1, sintered at three different sintering temperatures: 1000°C, 1100°C, and 1200°C has a common behavior among each three curves. In each case, the electric field (E) is decreasing very

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rapidly with increasing frequency of applied voltage. At the lowest frequency of 42 Hz, as would be expected, the sample sintered at 1100°C had the largest electric field followed closely by 1200°C, and lastly 1000°C.

As the frequency increases, the electric field for all three samples decreases very rapidly. This is a non-linear decrease that becomes less prominent with increasing frequency. After a threshold frequency of ~10,000 Hz the electric field values were all were near-zero. This demonstrates that at high frequencies the materials ability to sustain an electric field is greatly diminished. It is clear that the sintering temperature has a major impact on electric field behavior with frequency, especially at lower frequencies.

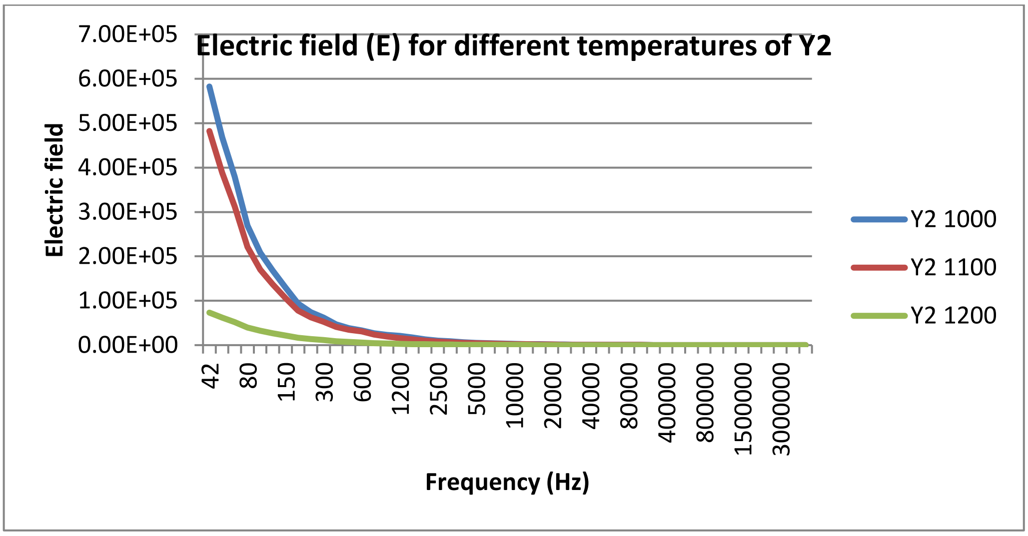

Figure (3-c): electric field (E”) against frequency for different temperatures of Y2

Figure (3-c) shows the graph "Electric field (E) for different temperatures of Y2" shows the electric field (E) vs frequency of a sample from the "Y2" that was sintered at three temperatures (i.e., 1000°C, 1100°C, 1200°C).
As the frequency goes up, the electric field (E) declines significantly, which is a common event for all three curves. The sample that was sintered at 1000°C has the highest electric field value at the lowest frequency shown on the graph (that is, 42 Hz). The samples that were sintered at 1100°C and 1200°C follow next in the electric field values.

As the frequency goes up, the electric field for all samples drops quickly. This drop is not linear and gets less noticeable at higher frequencies. The electric field values for all samples get very close to zero after about 10,000 Hz. This behavior implies that the material's ability to hold an electric field is very diminished at higher frequencies. The data illustrated that the effect of the sintering temperature on the electric field drastically changes the properties of the electric field, and this is further emphasized by the lower frequencies.

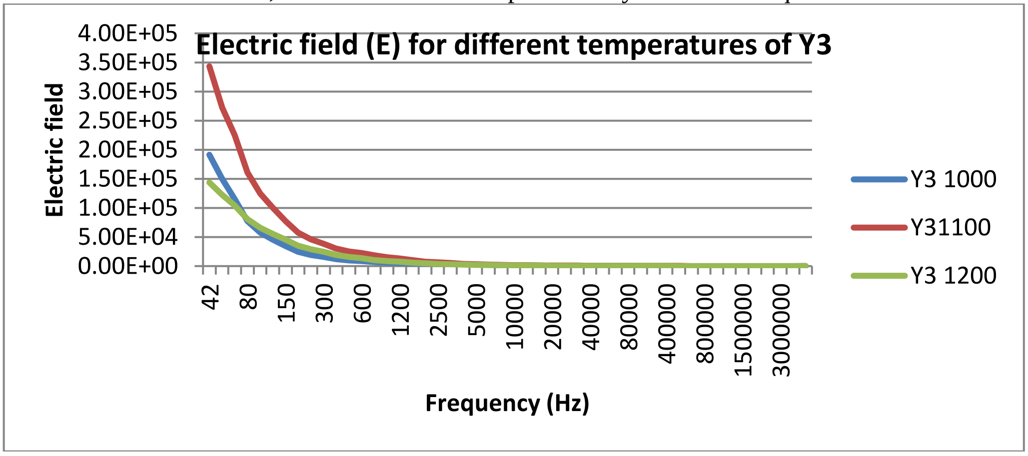

Figure (3-d): electric field (E”) against frequency for different temperatures of Y3

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Figure(3-d) is titled "Electric field (E) for different temperatures of Y3", and here it is showing the electric field (E) variation with frequency for one sample called Y3. This Y3 was sintered at 1000 °C, 1100 °C, and 1200 °C. There is a general trend in all three figures: the electric field E falls rapidly as the frequency rises. At the lowest frequency shown (42 Hz), the electric field for the 1100 °C sample is the greatest values followed by the 1000 °C sample, then the 1200 °C sample.

As the frequency increased, the electric field declines rapidly for all of the samples. The decrease is non-linear, and as the frequencies rise the decrease is less pronounced. By approximately 10,000 Hz, the electric field values for all the different samples are all very near zero. This indicates that at higher frequencies the material has very little ability to maintain the electric field. The data shows that the sintering temperature has a very strong influence on the electric field properties, especially at lower frequencies.

All doping concentrations (Y0 to Y3) and sintering temperatures show a clear trend: as frequency increases, electric field (E) decreases sharply to nearly zero by 10,000 Hz. This is characteristic of varistors, which lose polarization response rapidly at high frequencies.

Interestingly, for undoped (Y0) samples, the best low-frequency electric field was in the sample sintered at 1100°C, and the sintered 1000°C sample was nearly the same. The Y0 sample heated to 1200°C seemed to show very little electric field value at any frequency, meaning there was likely a significant change to the electrical behavior of this sample, likely an increase in conductivity, or a large depression of the interfacial polarization. For the 0.5% yttrium doped (Y1) samples, the sample sintered at 1100 °C was the maximum low-frequency electric field, the samples sintered at {1200 °C, and 1000 °C followed with lower electric fields in that order. Overall, while each temperature for Y1 samples gave the best electric field, they were consistently lower than the Y0 samples at each frequency.

Regarding the 1% Y_2O_3 group (Y2), the sample sintered at 1000°C has the highest electric field at lower frequencies and the 1200°C variant has the lowest electric field at lower frequencies. This may indicate that higher dopant concentrations start to interfere with charge movement, possibly altering residual grain boundary properties.

The 1.5% doped group (Y3) displays the same trends, with the 1100°C sample having the high electric field strength values at low frequency, the 1000°C sample next, and the 1200°C sample coming last. Despite the 1100°C sample outperforming the 1200°C sample in frequency, their low frequency values are still considerably lower than Y0 and Y1.

From an energy-efficent perspective (i.e., reducing energy waste and thermal rise), one sample stands alone in its current state: Y0 sintered at 1200°C. Its electric field values were consistent, remaining low on a flat slope across all frequencies. This demonstrates a significant change in its internal structure; likely significantly improving dielectric functionality, indicating very poor electrical loss for any applications where you may not want electrical loss.

2-2-Resistance (Rp)

The higher the resistance, the better it is for the varistor in general, since Rp keeps leakage current to a minimum and saves on power loss while maintaining the stability and lifetime of the device. However, the value that will be selected for Rp has to be picked correctly in conformity with the varistor application. Rs p changes with frequency because there are interactions within the dielectric properties, thermal effects, skin effect, and the intrinsic characteristic of the material. Its variation needs to be known so that one can model accurately and design electrical components and systems accordingly.

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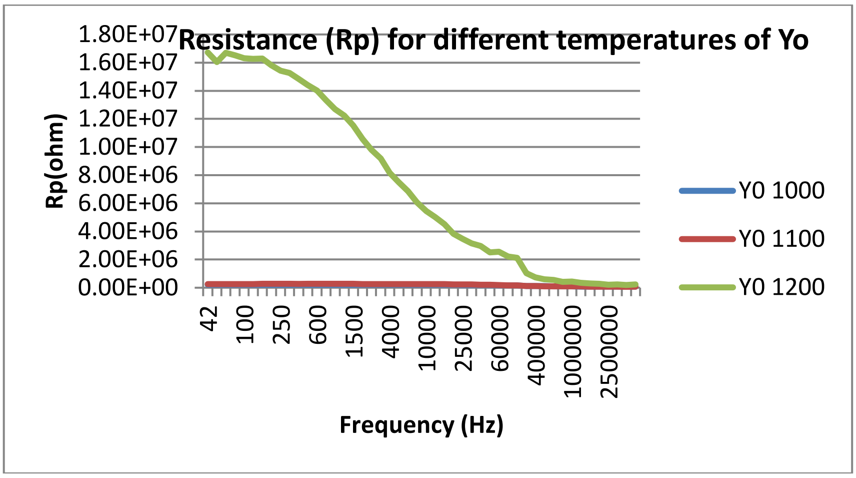
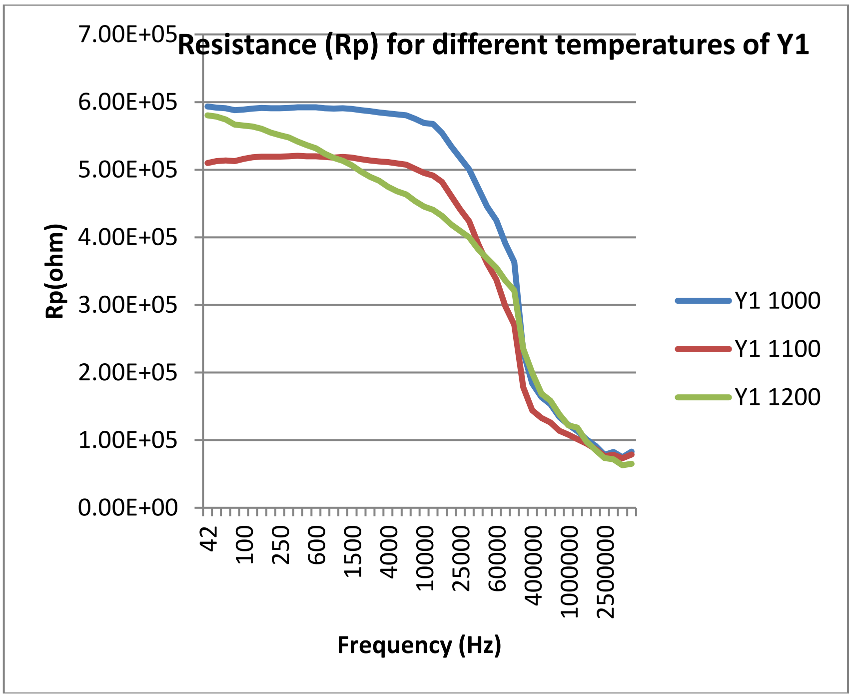


Figure(4-a) Rp (ohm) for different temperatures of Y0

Figure 4-a, entitled "Resistance (Rp) for different temperatures of Yo", shows the effect of resistance (Rp) depending on frequency of a sample labeled as Y0, sintered for three different temperatures: 1000°C, 1100°C, and 1200°C. A strong and consistent trend is seen in each of the three curves: resistance (Rp) decreases with an increase in frequency. For the lowest frequency shown (42Hz), the sample sintered at the highest temperature (1200°C) has the highest resistance, starting just above 1.6×107Ω. The samples sintered at 1000°C and 1100°C start with much lower and similar values for resistance at low frequencies, both below 0.5×106Ω. After starting with higher resistance, the resistance for the 1200°C sample experiences a rapid and non-linear decline as frequency increases, becoming lower by orders of magnitude. The 1000°C and 1100°C samples remain relatively low in resistance and stable for lower frequencies, and then again decline as frequency increases. About 100,000Hz the resistance values for all samples get close to one another and approach zero, with overall very low resistance yet indicating each sample possessed resistance at high frequencies. The data indicates that the temperature for sintering had a considerable effect on resistance behavior, particularly at lower frequencies, with the highest initial resistance value for the 1200°C in Y0-1200°C opposed to the other 2 temperatures.



Figure(4-b) Rp (ohm) for different temperatures of Y1

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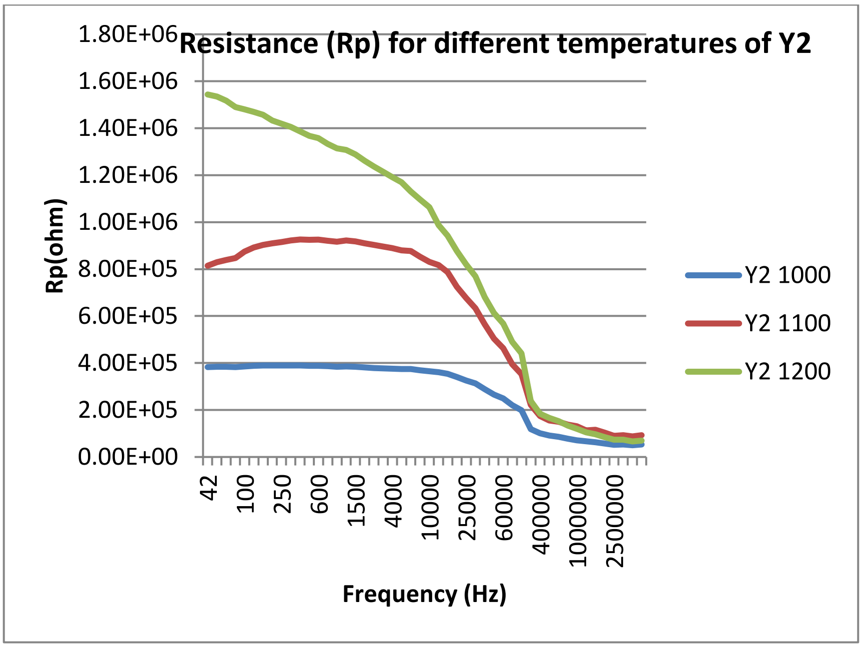
Figure (4-b) shows, "Resistance (Rp) for different temperatures of Y1, " depicts resistance(Rp) across frequency for one sample marked Y1, that was sintered at three optimization temperatures of 1000°C, 1100°C, and 1200°C The results produce a consistent trend in all three curves, resistance(Rp) reduces as frequency increases. At the lowest frequency shown (42 Hz), the sample sintered at 1000°C is displaying a very high resistance value, nearly 6.0×105Ω. The sample sintered at 1200°C starts slightly less, around 5.8×105Ω, and the 1100°C sample starting around 5.1×105Ω.

As frequency increases, the resistance measurements of all the samples display a relatively stable period at lower frequencies before a more considerable drop. Whereby, there is a drop in resistance across the board for all resistors, perhaps the greater drop in resistance could observed from the region of approximately 10,000 vs 100,000 Hz; however after approximately 100,000 Hz the resistance of all samples all converge to resistances approaching one-order of magnitude low or lower than approximately 1.0×105Ω . Thus, we can see the resistance is notably lower from at high frequencies, and we can see there is a possibility frequency is the dominant factor at high frequencies rather than the temperature of sintering when measuring at low frequencies.

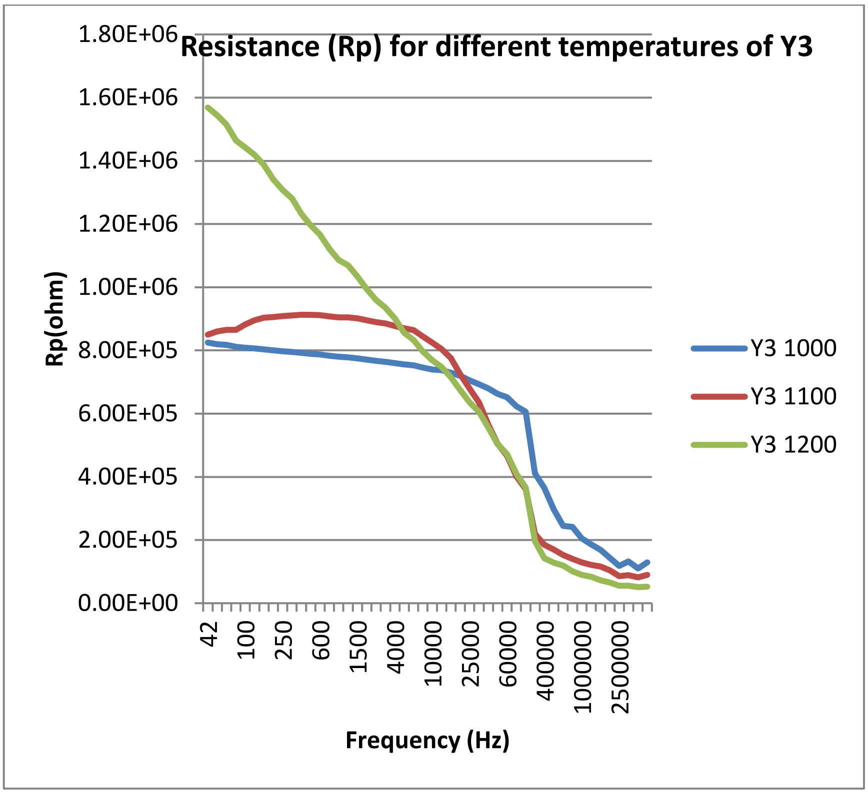
The resistance data is indicating the sintering temperature has the largest consequences of factors at lower frequencies, however the high frequencies are inconclusive with regards to the higher ordered resistances having specific behaviours which emerge with ero computing only the 1200°C sample had similar resistances at each frequency.



Figure(4-c) Rp(ohm) for different temperatures of Y2

Figure 4(c) presents the graph entitled "Resistance (Rp) for different temperatures of Y2", which displays resistance (Rp) versus frequency for the sample Y2, sintered at 1000°C, 1100°C, and 1200°C, respectively.
The 3 curves displayed all show a fairly consistent trend, clearly the resistance (Rp) decreases with increasing frequency. At the lowest frequency on display (42 Hz), the 1200°C sample has the maximum amount of resistance starting above 1.5×106Ω, the 1100°C sample starts out at 8.0×105Ω then has a slight increase followed by a decrease in resistance, accordingly the 1000°C sample starts out at around 4.0×105Ω and is fairly level at the lower frequencies.

The 1200°C sample exhibits a rapid decrease in resistance and abruptly, non-linear characteristics as frequency increases. The 1100°C sample, while also exhibiting a rapid decrease, plateaued at lower frequencies. The 1000°C sample presents lower resistance which remains stable until the high frequency portion of the data. After approximately 100,000 Hz, the resistance values for all 3 samples converged to a lower resistance level approaching 1.0×105Ω or lower, indicating very low resistance at the highest frequencies. Thus the data suggests that the temperature at which the samples were sintered had a significant impact on the resistance data, particularly at the lower frequency regime.



Figure(4-d) Rp(ohm) for different temperatures of Y3

Figure 4-d presents "Resistance (Rp) for different temperatures of Y3" and shows the dependence of resistance (Rp) on frequency for a sample Y3 sintered at three temperatures: 1000°, 1100°, and 1200°.

Across the three curves there is an overall decrease in resistance (Rp) as frequency increases. For the minimum frequency shown (42 Hz), the 1200° sample has the largest resistance value starting slightly above 1.5x106Ω, the 1100° sample starts around 8.0x105Ω, and the 1000° sample also starts around 8.0x105Ω.

The 1200° sample has the key behavior in that the resistance decreases quickly, and non-linearly, with increasing frequency. The 1100° sample increases slightly at the beginning of the test before starting its more dramatic decrease, whereas the 1000° sample starts at lower resistances and stays about constant until it begins to decrease at the very high frequencies. Starting at about 100,000 Hz and above, all of the resistance of the samples converge towards the same low value (~1.0x105Ω), suggesting that resistance is quite low at high frequencies and minimizing the effect of the sintering temperature. Referring back to Table 2, it is clear that the temperature during sintering has a significant effect on the resistance characteristics, especially at lower-frequency operation.

All samples tested at all concentrations (Y0, Y1, Y2, Y3) and sintering temperatures (1000°C, 1100°C, 1200°C) hold the same general trend where both Electric Field (E) and Resistance (Rp) are high initially but decrease significantly as frequency increases for both E and Rp until they reach nearly zero values, each at very high frequencies (higher than roughly 10,000 Hz for E and higher than 100,000 Hz for Rp). When considering electric field, the Y0 – 1200°C is a unique sample as it is at a low amount of electric field, nearly zero through the entire frequency range, which suggest that it may burly behave as a an insulator or may reflect a material that has very high conductivity or has an extremely low dielectric response. Similarly, in relation to resistance, the Y0 - 1200°C is also identified as the most appropriate for high voltage varistor applications. It has the highest resistance, by far, two orders of magnitude, higher than 1.6 x 107Ω (42 Hz), which is important under normal operating conditions to minimize current leakage. The Y0-1200°C showed the greatest, most direct and non-linear depreciation with frequency change in resistance, which reflects a suitable varistor behaviour as it characterized the behavior of going from an extremely resistive state to an extremely conduct state very resoundingly during a surge event. This dual characteristic of Y0-1200°C—maintaining a minimal electric field while possessing a very high initial resistance that sharply drops with frequency—underscores its superior performance for high voltage varistor applications, indicating an optimal balance for minimizing energy loss during normal operation and effectively clamping surges.

3- Impedance Z”(ohm)

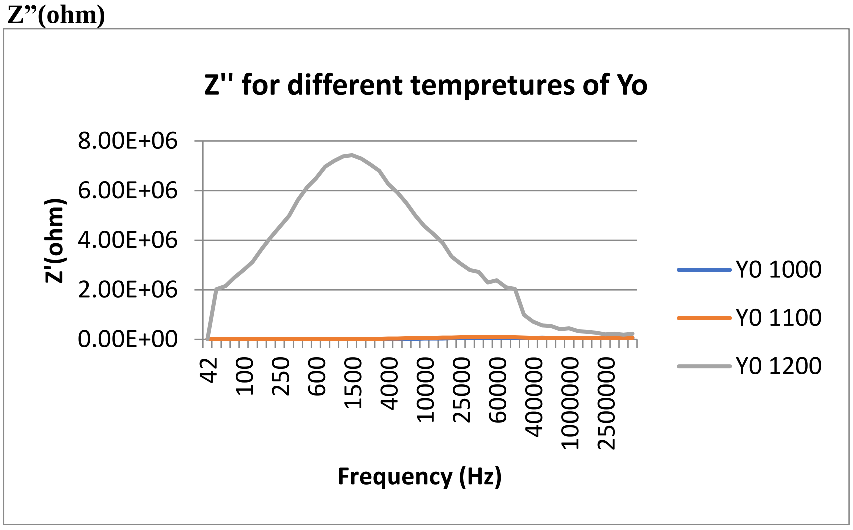


Figure (5-a): Z”(ohm) against frequency for different temperatures of Y0

Fig. 5(a) displays "Z" for different temperatures of Y0", illustrates the variation of the imaginary part of impedance (Z") as a function of frequency for a sample labeled Y0, sintered at three distinct temperatures: 1000°C, 1100°C, and 1200°C.

A clear difference in behavior is observed among the samples. For Y0-1000°C and Y0-1100°C, the Z" values remain very low, practically near zero across the entire frequency range, indicating a minimal reactive component to their impedance. In stark contrast, the sample sintered at 1200°C (Y0-1200°C) exhibits a prominent peak in Z". Starting from a low value at 42 Hz, Z" for Y0-1200°C rapidly increases, reaching a maximum value of over

$7.0\times10^{6}\Omega$ among 1500 Hz and 4000 Hz. Post-peak, Z" for Y0-1200°C drops rapidly as frequency increases, approaching values near-zero above approximately 400,000 Hz. This behavior, especially the distinct peak for Y0-1200°C, is typical of dielectric relaxation processes, or space charge polarization, where storage or dissipation of energy by the material occurs if frequency is varied. The absence of a peak in the 1000°C, and 1100°C, samples indicates that these relaxation phenomena are either absent or occur at frequencies below the measurements were taken at, or their magnitude is such that it is negligible - most likely due to either varied conductivity or differing microstructure of the material in Y0-1000°C and Y0-1100°C at lower sintering temperatures..

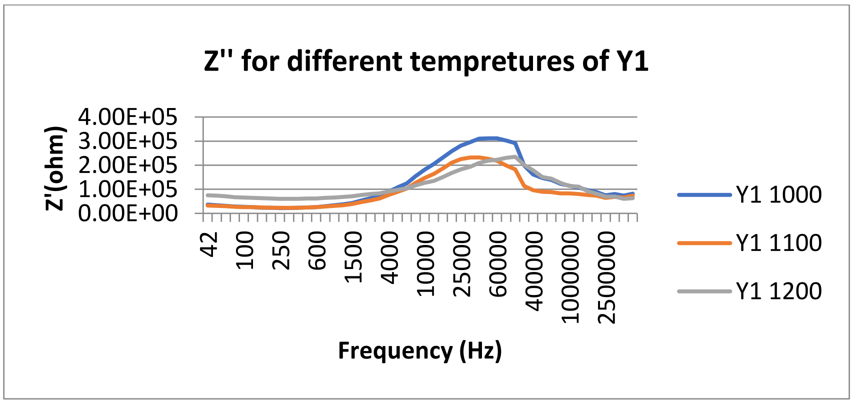


Figure (5-b): Z”(ohm) against frequency for different temperatures of Y1

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The graph labeled "Z" for Y1" is shown in figure (5-b) indicating the imaginary part of impedance (Z") in relation to a sample identified as Y1 that had been processed at three different temperatures (1000°C, 1100°C, and 1200°C). All samples exhibited a similar online trend where Z" had an increasing value with frequency that peaked sharply and dropped off as frequency continued to increase. Y1-1000°C had the largest peak, greater than 3.0×105Ω between the frequencies of 25000 Hz and 30000 Hz. Y1-1100°C had a peak close to 2.3×105Ω just prior to reaching 25000 Hz. Y1-1200°C had a peak close to 2.3×105Ω between the frequencies of 25000 Hz and 30000 Hz, however, it is overall curve starts at a higher Z" value at the low end of frequency than both Y1-1100°C and Y1-1000°C. In all cases, after reaching their respective peaks, the Z" of all samples fell off as frequency continued to increase, and appears to be approaching lower values at an approximate frequency of ≥ 250000Hz. This behavior is characteristic of dielectric relaxation processes, or space charge polarization processes where the material can change dramatically in how it stores or dissipates electricity, like with the occurrence of peaks in Z" at particular frequency sweeps. This section was also characterized by the peaks position and height being influenced by the sintering temperature.

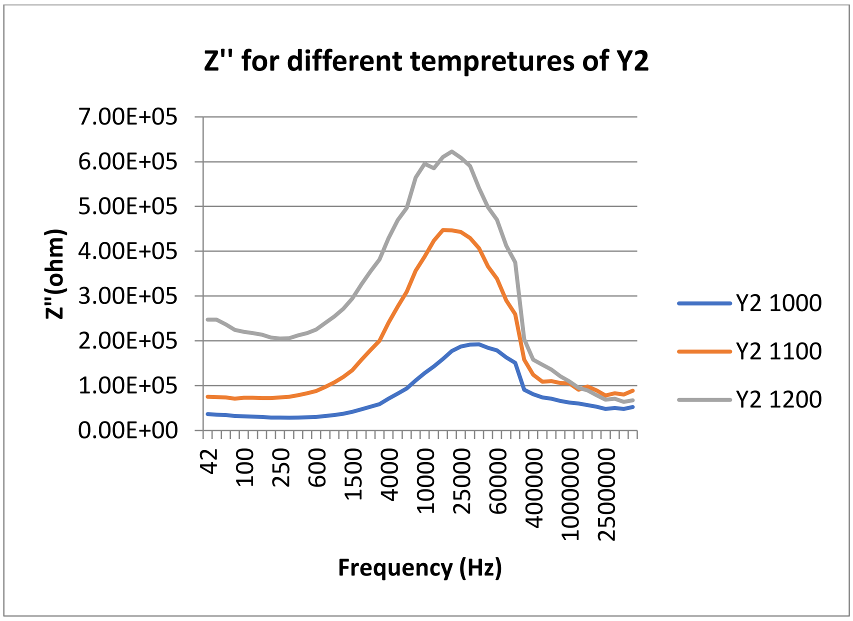

Figure (5-c): Z"(ohm) against frequency for different temperatures of Y2

Figure (5-c), which shows "Z◌ّ◌ُ"" for different sintered temperatures "Y2", presents the behavior of the imaginary component of impedance (Z"), as a function of frequency, for a sample indicated as "Y2", which was sintered in three distinct temperatures, "1000°C SINTERED", "1100°C SINTERED", and "1200°C SINTERED". The Z" for all samples showed an initial increase with frequency up to a pronounced peak before decreasing. The Y2-1200°C sample (highest peak) reached a value of over 6.0×105Ω, where the pronounced peak occurred around 25000 Hz. The Y2-1100°C sample showed an approximate peak of 4.5×105Ω, also at around 25000 Hz. The Y2-1000°C sample showed the lowest peak, approximately a value of 2.0×105Ω, near the same order of magnitude as the others and again occurred around 25000 Hz. After these pronounced peaks, but only for Y2-1200°C and Y2-1100°C, Z" again decreased to lower values as frequency increased further, with Z" approaching lower values at frequencies greater than about 400,000 Hz. This is consistent with the relaxation processes expected from dielectric relaxation or space charge polarization; where the material exhibited a clear and distinct factor of frequency that changed the mechanism of energy storage or dissipation, at a rate that appeared to be attendant to changes in frequency, and that the local maxima and extend was appreciably dictated by the sintering temperature variables.

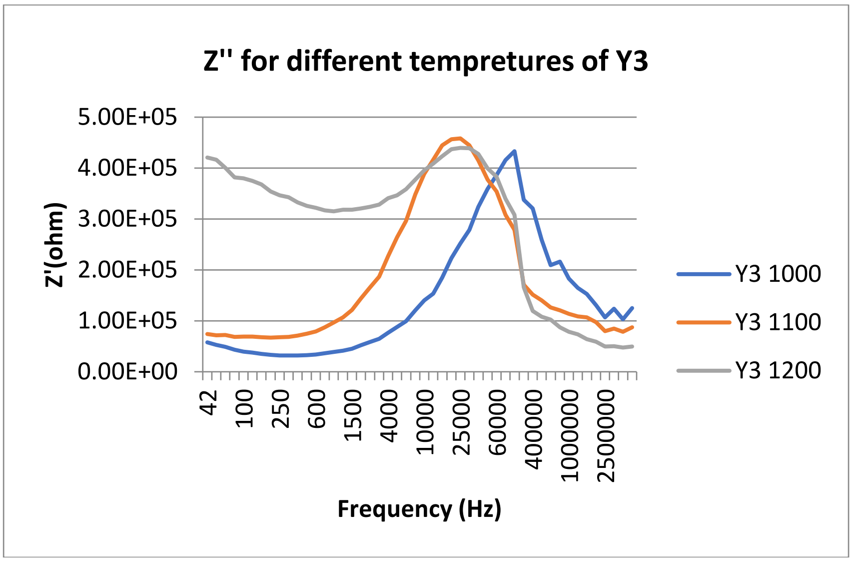

Figure (5-d): Z"(ohm) against frequency for different temperatures of Y3

Figure (5-d), "Resistance (Rp) for different temperatures of Y2," demonstrates the change in resistance (Rp) as a function of frequency (Hz) for a sample of Y2 sintered at 1000°C, 1100°C, and 1200°C. It is clear from the data that at lower frequencies the resistance (Rp) for all samples is significantly higher than at higher frequencies and as each of the complementary sintering temperatures increases the initial measured resistance (Rp) also decreased. For example, the sample Y2-1200°C represented the highest resistance (Rp) at 42 Hz, with an initial measured value over 1.5×106Ω at low frequencies. The sample Y2-1100°C did start with a very slight initial increase at the beginning of the frequency ramp, but then decreased some over the range of frequencies before plateauing at a reasonable frequency, around 8.0×105Ω. Specifically the sample Y2—1000° started with an initial measured resistance (Rp) equal to 4.0×105Ω and when compared to the other samples stays relatively constant over the lower frequency in the experimental data presented in Figure (5-d). The resistance (Rp) for the sample Y2—1200 the drop off rate at high frequencies represents a very sharp non-linear decrease and the sample Y2-1100 also shows a very significant decrease. The sample Y2-1000 however, remained more stable towards a much lower resistance (Rp) for the initial frequencies and the resistance value did not decrease substantially until the last few frequencies. By the time the samples approached approximately 100.000 Hz frequency for all samples the resistance values all coalesce at a frequency indicative of significantly less resistance (Rp) or lower values typically around 1.0×105Ω or less. And while there are certainly differences with regard to the resistance behavior of the samples due to varying initial sintering temperature and subsequent sample temperature behavior the results are clear when viewing the resistance (Rp) as a function of frequency presented.

The graphs provided from the data, shown in terms of "Z" at different temperatures Y1," "Z" at different temperatures Y2," "Z" at different temperatures Y0," (also saw info on Y3), illustrate or demonstrate the imaginary aspect of impedance (Z") as a function of frequency as it relates to a range of samples from each of the materials that were sintered at 1000°C, 1100°C, and 1200°C.

For most high voltage varistor applications, a strong Z" peak is often indicative of significant dielectric relaxation processes or space charge polarization, two processes which are essential to the nonlinear voltage-current characteristics of the material, as well as the materials ability to dissipate and absorb surge energy. A larger magnitude of the peak compiling with the high surface area of the material would be even a more effective means of attenuating transient energy. When looking at the Z" values of the different concentrations, the Y0-1200°C samples had an exceptionally large and pronounced Z" peak of greater than 7.0×106Ω between 1500 Hz and 4000 Hz, which is greater—by one or more orders of magnitude—than any of the peaks of the Y1, Y2, or Y3 samples combined.. This indicates a much stronger dielectric relaxation or space charge polarization process occurring within the material at this specific concentration and sintering temperature. This highest peak magnitude signifies a superior capacity for enhanced energy storage and dissipation, which is essential for absorbing and dissipating the substantial energy associated with voltage surges in high voltage varistor applications. **Therefore, the Y0-1200°C sam**ple is selected as the best for high voltage varistor applications based on its Z" characteristics due to its exceptionally high peak magnitude, suggesting superior dielectric relaxation and energy dissipation capabilities relevant for high voltage varistor applications.

2-4 Conductivity

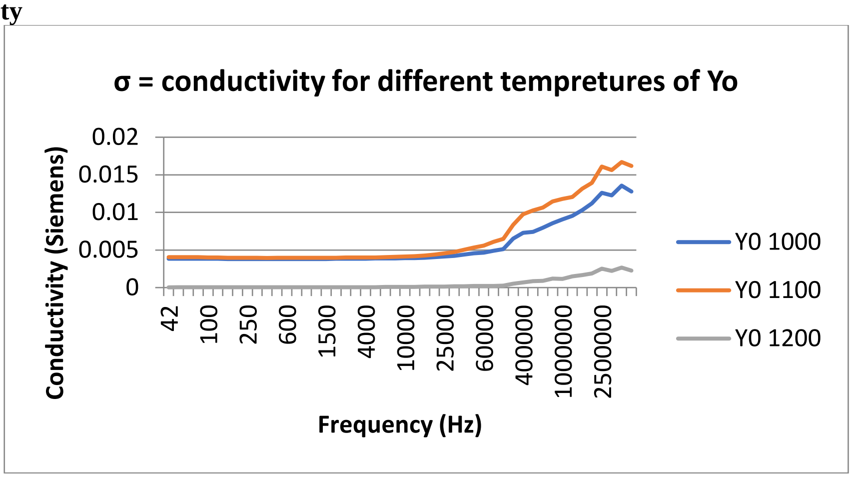

Figure (6-a): conductivity (Siemens) against frequency for different temperatures of Y0

Figure (6-a) shows The figure "σ = conductivity for different temperatures of Yo" illustrates the dependence of conductivity (σ) on frequency for a sample with the label Y0, sintered at 1000°C, 1100°C and 1200°C.

We see a clear and consistent trend for the 1000°C and 1100°C samples: the conductivity values remain fairly constant at lower frequencies (around 0.004Ω−1cm−1). As the frequency increases - especially past around 20,000 Hz, the conductivity for both Y0-1000°C and Y0-1100°C starts to increase sharply and non-linearly It is important to note that while Y0-1100°C had slightly greater conductivity values than Y0-1000°C reaching over 0.016Ω−1cm−1 with the highest frequency measured, the sample sintered at 1200°C (Y0-1200°C) has much lower conductivity values in the entire frequency range. Here conductivity was close to zero and essentially increased very gradually with frequency, with conductivity never increasing above approximately 0.0025Ω−1cm−1 even at the highest frequencies. This behavior would indicate defects in the material and that the sintering temperature drastically influences the conductive characteristics of the Y0 material (e.g., 1200°C yielded a much less conductive material than 1000°C and 1100°C, especially at lower frequencies). It is normal to observe some degree of increase of conductivity with frequency for all samples; this is very typical of AC conductivity in many dielectric and semiconducting materials and can be attributed to a hopping conduction process or the increased mobility of charge carriers at higher frequencies.

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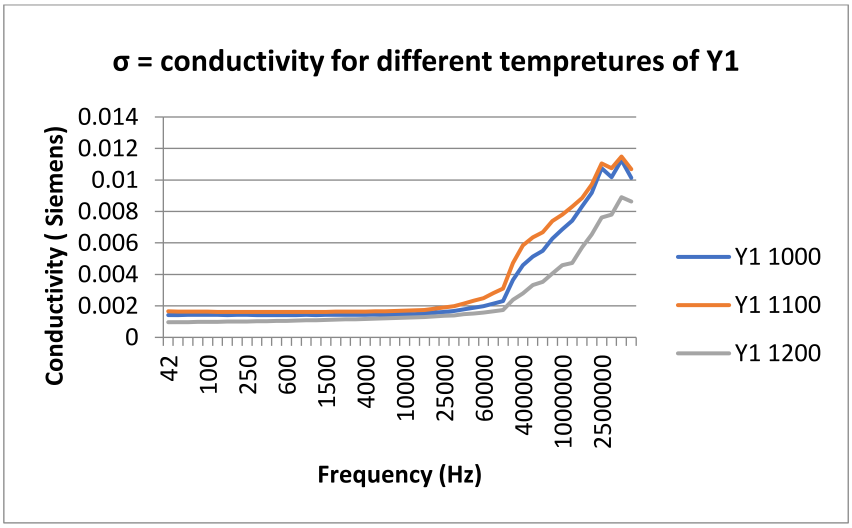

Figure (6-b): conductivity (Siemens) against frequency for different temperatures of Y1

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σ = conductivity for different temperatures of Y1", illustrates the variation of conductivity (σ) as a function of frequency for a sample labeled Y1, sintered at three distinct temperatures: 1000°C, 1100°C, and 1200°C.

In high voltage varistor applications, the conductivity profile is an important property. Ideally a varistor exhibits very low conductivity (high resistance) at low frequencies characteristic of the normal operation condition, so that no/limited leakage current passes and power loss is minimized. It should have a marked increase in conductivity at high frequencies (when surge events occur). This helps the varistor to effectively clamp transient voltages and dissipate energy.

For the Y1 samples, all three sintering temperatures present a very similar overall trend: their conductivity values are low and constant at lower frequencies, but then demonstrate a sharp and non-linear increase as frequency continues to increase, particularly after about approximately 20,000 Hz. In terms of low frequency, the Y1-1000°C and Y1-1100°C samples exhibit slightly higher conductivity at the initiation of testing (approximately 0.0015Ω−1cm−1) while the Y1-1200°C sample begins just slightly lower (where the conductivity starts at about 0.001Ω−1cm−1). As frequency increases, Y1-1000°C and Y1-1100°C show a more pronounced increase in conductivity, reaching values over 0.01Ω−1cm−1 at the highest frequencies. Y1-1200°C, while also increasing, maintains comparatively lower conductivity values across the higher frequency range, reaching about

0.009Ω−1cm−1. This behavior suggests that while all Y1 samples show the expected increase in AC conductivity with frequency, indicative of charge carrier mobility or hopping, the Y1-1200°C sample generally presents slightly lower conductivity across the frequency spectrum. This characteristic of lower conductivity, particularly at normal operating frequencies, is generally more desirable for high voltage varistor applications as it translates to higher impedance, thereby minimizing standby current and power dissipation.

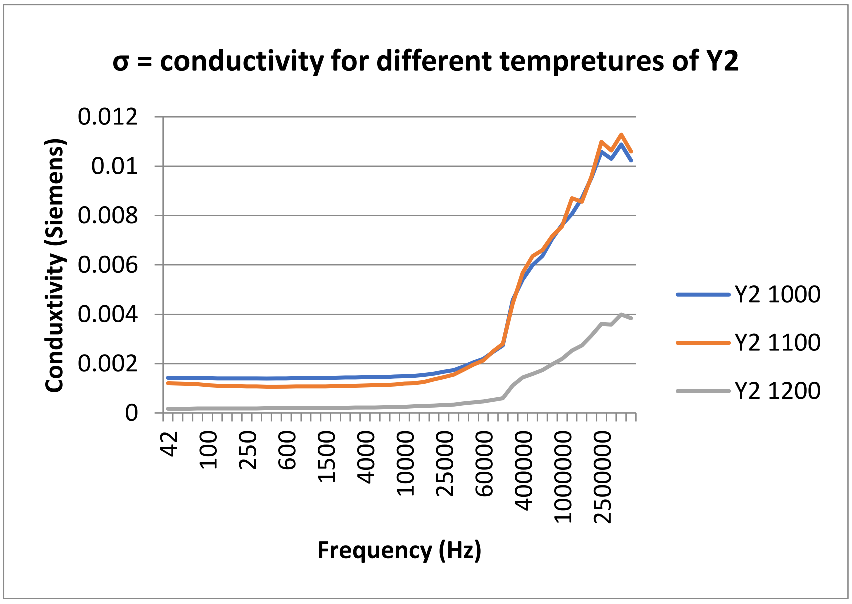

Figure (6-c): conductivity (Siemens) against frequency for different temperatures of Y2

The graph, "σ = conductivity for different temperatures of Y2", illustrates the variation of conductivity (σ) as a function of frequency for a sample labeled Y2, sintered at three distinct temperatures: 1000°C, 1100°C, and 1200°C.

In the context of high voltage varistor applications, the conductivity profile is a critical parameter. An ideal varistor should exhibit very low conductivity (high resistance) at low frequencies, corresponding to normal operating conditions, to minimize leakage current and power loss. Conversely, it should demonstrate a significant increase in conductivity at high frequencies, indicative of a surge event, to effectively clamp transient voltages and dissipate energy.

For the Y2 samples, there is a similar general trend among the three sintering temperatures regarding conductivity; they tended to remain low and relatively stable at lower frequencies and show a rapid, nonlinear increase as frequency increases, particularly after about 40,000 Hz. At low frequencies (e.g., 42 Hz), the Y2-1000°C and the Y2-1100°C samples show similar initial values of conductivity (approximately 0.0013Ω−1cm−1). The Y2-1200°C sample has a markedly lower initial value of conductivity, at approximately 0.0002Ω−1cm−1 at 42 Hz. The samples Y2-1000°C and Y2-1100°C exhibited a marked increase in conductivity with frequency, with each of these samples ultimately having conductivity greater than 0.01Ω−1cm−1 at the highest frequency intervals. The sample Y2-1200°C exhibits increased conductivity with frequency, but is consistently lower than the Y2-1000°C and Y2-1100°C samples throughout the entire frequency range; in fact, at the highest frequency intervals, the Y2-1200°C sample demonstrated approximately 0.004Ω−1cm−1. A field with consistent lower conductivity character of Y2-1200°C, especially at the standard operating frequencies, is very advantageous in high voltage varistor applications. A reduced conductivity indicates a larger impedance, which is required for lower standby current and power loss via improved impedance when a varistor is not clamping a surge. While it is a positive attribute as all Y2 samples demonstrate their ability to shift toward a more conductive state with increased frequency while helping to protect against surge via transient response.

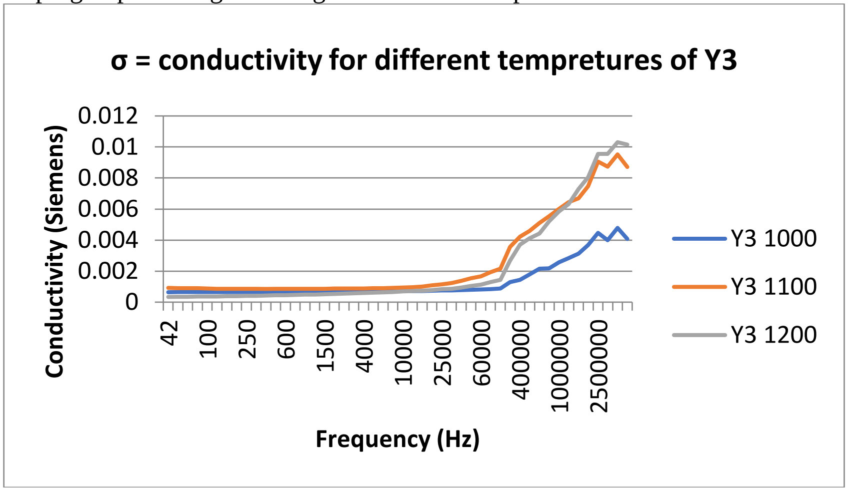

Figure (6-d): conductivity (Siemens) against frequency for different temperatures of Y3

Figure 6-d. labelled "σ = conductivity for different temperatures of Y3", shows the conductivity (σ) against frequency for a sample called Y3, which was sintered at three different temperatures (1000 °C, 1100 °C, and 1200 °C).

In high voltage varistor applications, the conductivity profile is an important characteristic. The ideal varistor will have a very small conductivity at low frequencies (high resistance), indicating normal operating conditions to have negligible leakage current and power loss, and a large increase in conductivity at high frequencies, indicating a surge event, and to clamp transient voltages to dissipate energy.

The Y3 samples have a general typical curve at each sintering temperature, for instance, in Figure 6-d, the conductivity values are low and stable at low frequencies and then sharply increase non-linearly at higher frequencies (noticeably after around 20,000 Hz).. The Y3-1200 °C sample also shows an increase in conductivity with frequency but still had relatively low conductivity results at all frequencies at measurement temperature and reached 0.01Ω−1cm−1 at the highest frequencies. This low conductivity exhibited by Y3-1200°C, especially at the normal operating frequencies is a critical feature for high voltage varistor applications. Lower conductivity, therefore, higher impedance, is desirable at normal operating frequencies in order to minimize standby current and power dissipation when the varistor is not clamping a surge. The fact that conductivity increases with frequency for all the Y3 samples is a strength by indicating that they can reliably transition to a more conductive material state during high frequency transient events, meeting the surge protection role. When reviewing the conductivity results for the Y0, Y1, Y2, and Y3 samples for high voltage (HV) applications, the ideal material for a varistor should demonstrate very low conductivity (high resistance) at low frequency to achieve minimal leakage current (and therefore power loss) in normal operation, and a substantially increased conductivity at high frequency to clamp transient voltages and dissipate the surge energy.

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Here's a comparison of the conductivity profiles:

- **Y0 Samples:** Y0-1000°C and Y0-1100°C demonstrate the initial steady state conductivities (which is the highest at lower frequencies: approximately 0.004Ω−1cm−1), however at elevated frequencies the data demonstrates very high conductivity (greater than 0.016Ω−1cm−1). Y0-1200°C has a very low conductivity (starting close to zero) and only increases to 0.0025Ω−1cm−1 at elevated frequencies.
- **Y1 Samples**: Y1-1000°C and Y1-1100°C have both initial conductivities of approximately 0.0015Ω−1cm−1 and both show want to increase over the elevated frequency range to greater than 0.01Ω−1cm−1. Y1-1200°C had a slightly lower than initial conductivity (around 0.001Ω−1cm−1 at low frequencies) was able to reach slightly around 0.009Ω−1cm−1 at elevated frequencies.
- **Y2 Samples**: Y2-1000°C and Y2-1100°C had starting conductivities of approximately 0.0013Ω−1cm−1 for both samples. Conductivity values reached above 0.01Ω−1cm−1 in elevated frequencies. Y2-1200°C is the only sample to keep a lower starting conductivity of about 0.0002Ω−1cm−1 (42 Hz). Y2-1200°C reaches a maximum conductivity of about 0.004Ω−1cm−1 at elevated frequencies.
- **Y3 Samples:** Y2-1000°C and Y2-1100°C have initial conductivity (real part of E) in the range of 0.0008Ω−1cm−1 to 0.0009Ω−1cm−1. Y2-1100°C had a maximum conductivity over 0.009Ω−1cm−1 and Y2-1000°C around 0.004Ω−1cm−1. Y2-1200°C had a starting conductivity at 0.0004Ω−1cm−1 and increased to around 0.01Ω−1cm−1 at the high frequencies.

From comparing these values, it is fairly clear that the Y2-1200°C sample is the best candidate for high voltage varistor applications.

There are several reasons for this statement:

- **Lowest Initial Conductivity:** The Y2-1200°C sample shows the absolute lowest conductivity at low frequencies among all tested materials (approximately 0.0002Ω−1cm−1 at 42 Hz). This property is a fundamental characteristic of high voltage varistors, as extremely low conductivity in standby mode allows for very low leakage current and negligible power dissipation. This reduces loss in the standby operating mode, benefiting the efficiency and reliability of the device!
- **High Increase with Frequency:** The Y2-1200°C sample, only having low baseline conductivity, also demonstrates a very high increase (20 times greater than the initial value at 0.004Ω−1cm−1) conductivity with increasing frequency. This is very important for the varistor to successfully switch from highly resistive to a highly conductive state, and for the device to clamp transient voltages and dissipate energy during the surge event.
- **Best Overall**: In conclusion, the Y2-1200°C sample combines the very low impact (standby leakage) of a varistor during normal operation with sufficient energy absorbing characteristics for surge events. Although other samples like Y3-1200°C had higher absolute conductivity values at high frequencies, the Y2-1200°C sample has enough (low-frequency and low-value) performance to be preferable in applications that worry about leakage current without compromising its ability to respond to the surge.

2-5 Dielectric constant εr

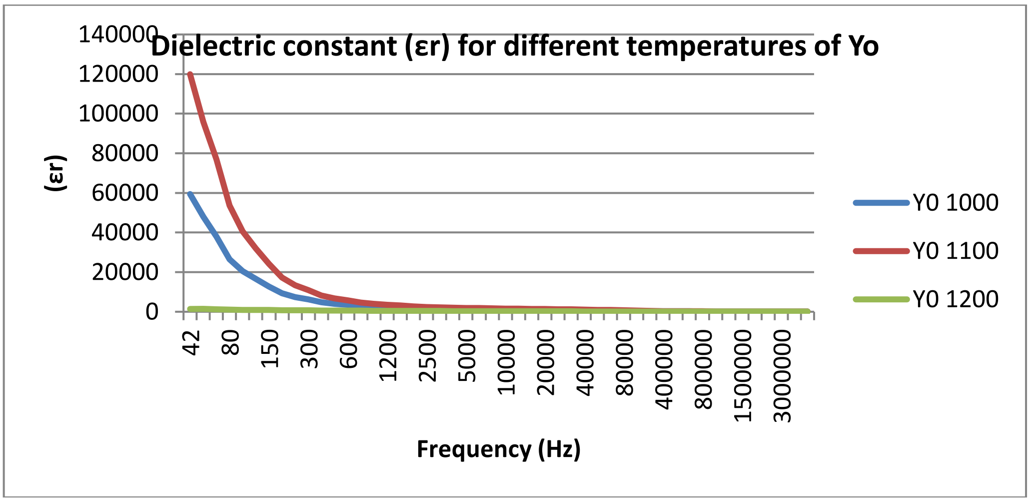

Figure (7-a): dielectric constant against frequency for different temperatures of Y0

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Figure (7-a) shows The graph, titled "Dielectric constant (εr) for different temperatures of Yo", illustrates the variation of the dielectric constant as a function of frequency for a sample labeled Y0, sintered at three distinct temperatures: 1000°C, 1100°C, and 1200°C.

In the context of high voltage applications, the dielectric constant is crucial as it directly relates to the material's capacitance (C=ϵA/d). For varistor materials, particularly at low frequencies (normal operating conditions), a lower dielectric constant is generally desirable. This is because lower capacitance contributes to lower capacitive leakage currents (IC=ωCV), thereby minimizing power loss and enhancing the efficiency and reliability of the high voltage device during standby.

A clear trend is observed where the dielectric constant for all Y0 samples decreases sharply with increasing frequency, which is typical for dielectric materials as various polarization mechanisms cease to follow the alternating field at higher frequencies.
Specifically:

- **Y0-1100°C** sample has the highest dielectric constant at low frequencies, starting at above 120,000 and then decreasing rapidly.
- **Y0-1000°C** sample has the second highest dielectric constant, starting around 60,000 and decreasing rapidly as frequency increases.
- **Y0-1200**°C sample shows much lower dielectric constant values throughout the frequency range, starting very low (around 2000 - 3000) and staying fairly low, even at high frequency.

The property of a consistently low dielectric constant for Y0-1200C is perfectly suited for high voltage varistor applications. In essence, the dielectric has a lower inherent capacitance, lower leakage currents, and less energy storage during normal operating conditions, which may allow the dielectric to respond faster due to lower inherent "charge storage". The dramatic drop in dielectric constant due to the 1200C sintering temperature suggests a significant reorganization of the microstructure, or proud in this case the charge storage mechanisms, better maintaining high impedance for high voltage conditions.

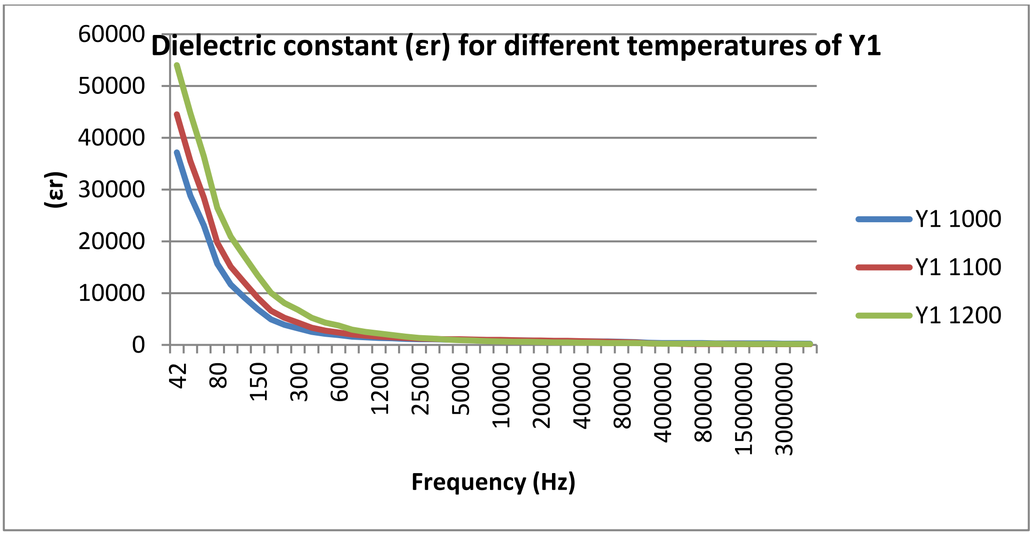

Figure (7-b): dielectric constant against frequency for different temperatures of Y1

The graph titled "Dielectric constant (εr) for different temperatures of Y1" displays these dielectric constants as functions of frequency for Y1, which was produced by sintering at three different temperatures: 1000°C (T1), 1100°C (T2), and 1200°C (T3).

The dielectric constant matters in high voltage applications because it is directly proportional to capacitance. For varistor materials, and more specifically at low frequencies (normal use conditions), it is preferred to have a lower dielectric constraints. Having a lower dielectric constant contributes to lower capacitance which will result in lower capacitive leakage currents, lower power loss, and higher efficiency and reliability of the high voltage device when in a standby condition.

A clear trend also exists for the dielectric constants of Y1 that all the samples agree with in terms of how the dielectric constant decreases quickly with frequency. This is the most common trend in dielectric materials, and is due to the decreasing ability of different polarization mechanisms to follow the time-varying field at increased frequencies.

Specifically:

- **Y1-1200°C sample** exhibits the highest dielectric constant at low frequencies, starting above 50,000 and decreasing rapidly.
- **Y1-1100°C sample** has the second highest dielectric constant, starting around 45,000 and also decreasing sharply with frequency.
- **Y1-1000°C sample** displays the lowest initial dielectric constant values, starting around 37,000, and also shows a rapid decrease with increasing frequency.

This behavior indicates that for Y1, lower sintering temperatures lead to lower initial dielectric constants. While all samples show the characteristic decline in ϵr with increasing frequency, the Y1-1000°C sample, by having the lowest dielectric constant at low frequencies, would contribute least to capacitive leakage current during normal high voltage operation, which is a favorable characteristic.

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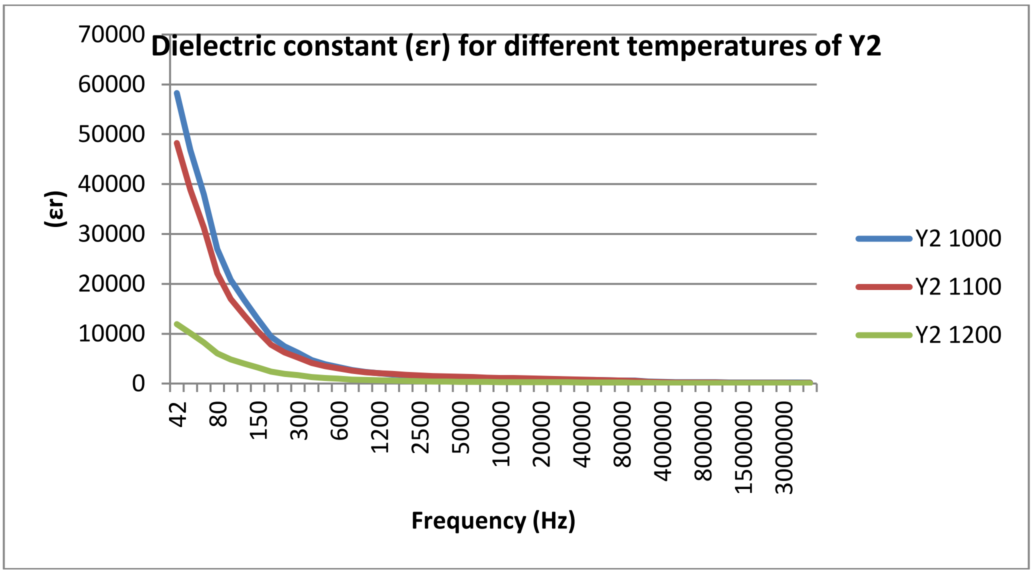

Figure (7-c): dielectric constant against frequency for different temperatures of D2

Figure (7-C) shows The Graph called "Dielectric constant (ϵr) for different temperatures of Y2" shows the dielectric constant as a function of frequency for the sample identified as Y2, which was derived from being sintered at three different temperatures: 1000°C, 1100°C, and 1200°C.

The dielectric constant is important for high voltage applications because it directly relates to capacitance. For varistor materials, it is desirable to have a low dielectric constant, especially at low frequencies (which means it is manageable at normal operation), because a lower capacitance means lower capacitive leakage currents – basically this allows for the least amount of power loss, which positively impacts the efficiency and reliability of the high voltage device while on standby.

There is an obvious trend showing that the dielectric constant for all samples of Y2 decreases dramatically as the frequency increases, which is expected behavior for dielectric materials where several polarization mechanisms can't keep up with the alternating field above higher frequencies.

Specifically:

- **Y2-1000°C sample** exhibits the highest dielectric constant at low frequencies, starting above 58,000 and decreasing rapidly.
- **Y2-1100°C sample** has the second highest dielectric constant, starting around 48,000 and also decreasing sharply with frequency.

- **Y2-1200°C sample** exhibits significantly lower initial dielectric constant values, starting at just over 12000, and a quicker decrease with frequency, leading to the values staying the lowest throughout the measured frequency range.

At 1200°C sintering temperatures, Y2 should exhibit significantly lower initial dielectric constant values than 1000° and 1100°. This suggests that the dielectric constant of Y2 has been significantly low from the beginning. especially at low frequencies, is valuable for high voltage varistor applications because it represents lower inherent capacitance. This feature assists with achieving negligible capacitive leakage current during normal high voltage operation whilst obtaining higher efficiency and lower standby power dissipation.

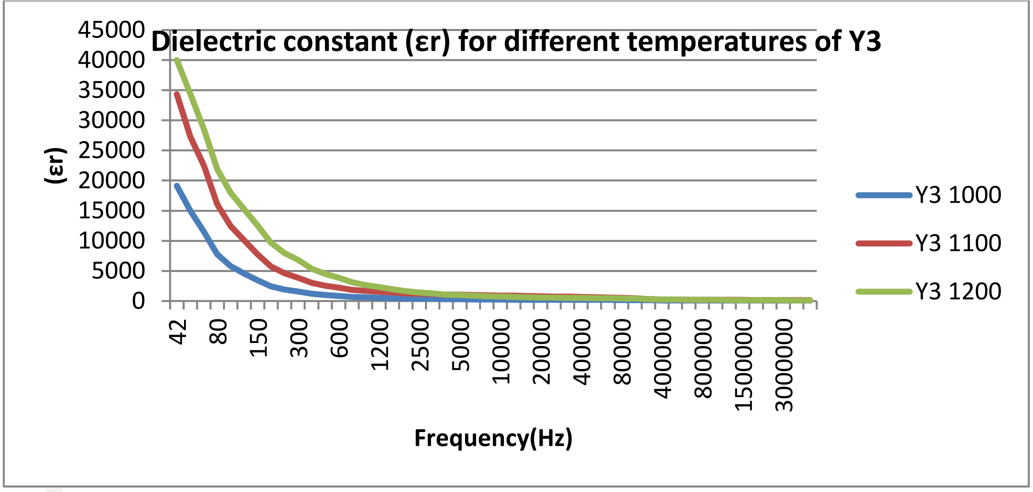

Figure (7-d): dielectric constant against frequency for different temperatures of Y3

Figure 7-d provides an overview of what is known as "Dielectric constant (εr) for different temperatures of Y3" indicating the dependance of dielectric constant on frequency for the Y3 sample, sintered at 1000 °C, 1100 °C, and 1200 °C.

In high voltage applications a low dielectric constant at low frequencies is most desirable. The low dielectric constant will lead to low capacitive leakage current (IC=ωCV), reduced power loss, and higher efficiency in standby operation of the device.

The pattern shown on the graph indicates that the dielectric constant for all Y3 samples rapidly decrease with increased frequency. This behaviour is typical of dielectric material as various polarization mechanisms fail to follow the rapidly alternating electric field as frequency increases.

Specifically:

- **Y3-1200°C sample** exhibits the highest dielectric constant at low frequencies, starting at approximately 40,000 and rapidly decreasing.
- **Y3-1100°C sample** has the second highest dielectric constant, starting around 35,000 at low frequencies and showing a similar rapid decline.
- **Y3-1000°C sample** shows the lowest initial dielectric constant values in this series, starting at approximately 20,000, and also decreases sharply with increasing frequency.

This behavior suggests that for the Y3 composition, lower sintering temperatures will have a lower initial dielectric constant. Thus, for high voltage varistor applications, the Y3-1000°C sample, because it has the lowest dielectric constant at low frequencies, would least contribute to capacitive leakage current during normal high voltage operation, which is a good trait to have.

From a high-voltage engineering perspective, the dielectric constant (εr) performance of the varistor samples Y0 to Y3, brings very important information regarding their design and operational productivity for a reliable and efficient surge protective device. It is particularly favorable to have low dielectric constant at low frequencies in order to mitigate capacitive leakage currents (IC = ωCV), reducing power losses from standby power consumption and improving performance of an electrical device under steady state power conditions. Of all the samples, Y0-1200°C and Y2-1200°C show any considerably lower dielectric constant (εr) values in the frequency range which promotes the most reliable and efficient surge protective device due to their low inherent capacitance and better insulating capacities. The other samples such as Y1-1200°C and Y3-1200°C show higher εr values which only further promotes higher energy loss because of their increased volume and response times and, therefore, are worse varistors for high voltage applications. These distinct trends confirm that the effect of sintering temperature on the microstructure of the material and dielectric properties of the specimens of interest, is clearly a critical factor in producing or improving varistor performance under high voltage operational conditions.

2-6 Dielectric loss tangent (tan δ)

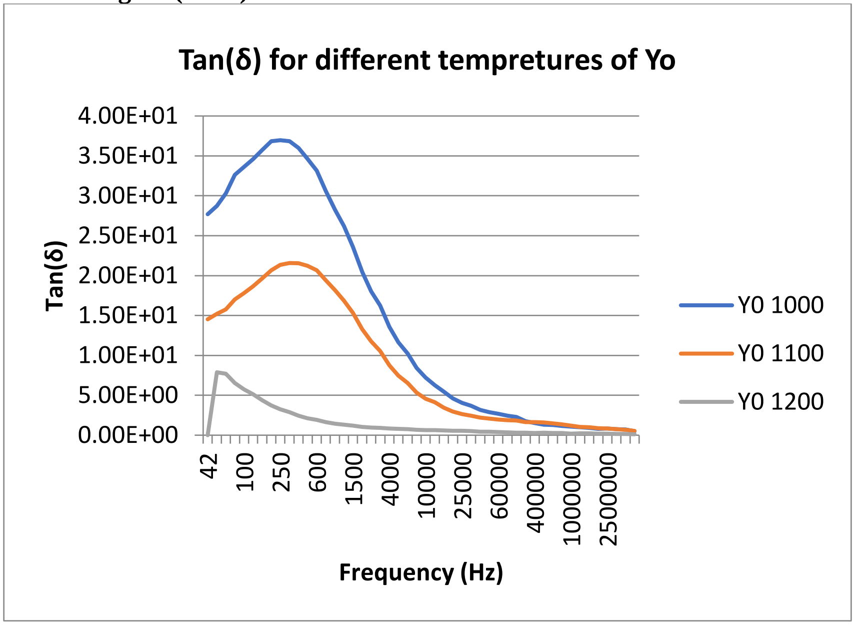

Figure (8-a): Tan(δ) plotted against frequency for different temperatures of Y0.

Figure (8-a), the graph "Tan(δ) for different temperatures of Y0" shows the dielectric loss tangent (Tan(δ)) versus frequency for the Y0 sample sintered at three distinct temperatures of 1000°C, 1100°C, and 1200°C.

In the field of high voltage engineering, low dielectric loss tangents are preferred, particularly at low frequencies. Tan(δ) represents the ratio of lost energy to stored energy within the dielectric material, meaning high Tan(δ) values indicate a lot of energy is being dissipated as heat, which will produce increased power loss, heating, and possible breakdown in high voltage devices.

The graph shows distinct behavior for each sintering temperature:

- **Y0-1000°C sample** exhibits the highest Tan(δ) values, starting around 28 and peaking significantly (above 35) before decreasing with increasing frequency.
- **Y0-1100°C sample** shows the second highest Tan(δ) values, starting around 15 and peaking around 21 before also decreasing with increasing frequency.
- In stark contrast, the **Y0-1200°C sample** displays significantly lower Tan(δ) values across the entire frequency range, starting below 10 and remaining consistently low, that fast approach to zero at high frequencies.

A lower Tan(δ) at high frequency is a positive feature of Y0-1200°C for high voltage applications. The lower value indicates that Y0-1200°C loses less energy as heat and thus less power loss, increases efficiencies and provides good thermal stability makes Y0-1200°C ideal for a high voltage application where performance and reliability should be maintained while limiting wasted energy and overheating.

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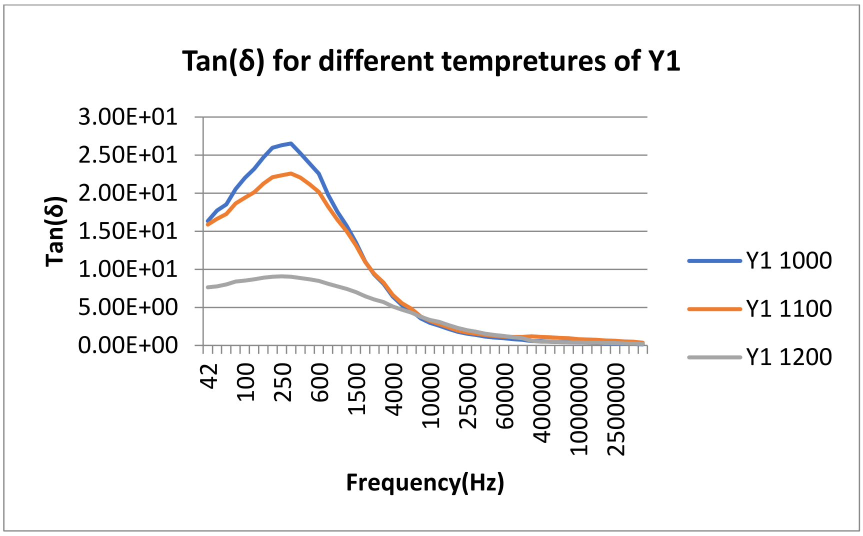

Figure (8-b): Tan(δ) plotted against frequency for various temperatures of Y1.

Figure 8-b, entitled "Tan(δ) at different temperatures of Y1," shows the dielectric loss tangent (Tan(δ)) as a function of frequency for the Y1 sample sintered at 1000°C, 1100°C, and 1200°C.

In high voltage applications, low dielectric loss tangent is preferred. Tan(δ) indicates the energy lost as heat in a dielectric. High Tan(δ) means much energy is lost as heat, resulting in increased power consumption, unwanted energy in the thermal region of the device, and degradation and/or breakdown of a high voltage device with time. From the graph, we can see two behaviors of the loss tangent depending on the sintering temperature:

- The **Y1-1000°C sample** exhibits the highest Tan(δ) values at low frequencies, starting around 16 and peaking significantly (above 25) before decreasing with increasing frequency.
- The **Y1-1100°C sample** shows the second highest Tan(δ) values, starting around 15 and peaking around 22 before also decreasing with increasing frequency.
- In contrast, the **Y1-1200°C sample** consistently displays significantly lower Tan(δ) values across the entire frequency range, starting below 10 and remaining remarkably low, approaching zero at higher frequencies.

This attribute of a consistently lower Tan(δ) for Y1-1200°C is very advantageous for high voltage applications. It means that this material will lose considerably less energy as heat, which equates to reducing power losses, improved efficiency of operation with increases stability and reliability when put into a stressed high voltage application..

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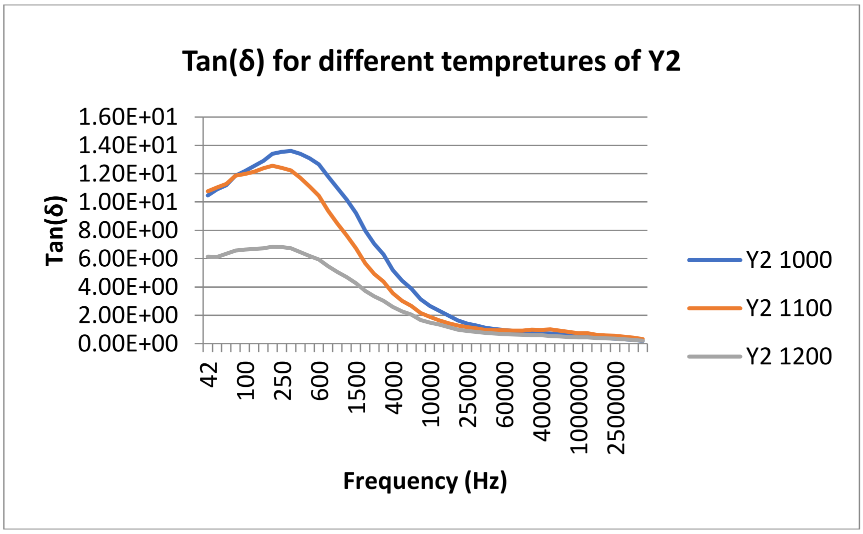

Figure (8-c): Tan(δ) plotted against frequency for various temperatures of Y2.

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The graph displays the dielectric loss tangent (Tan(δ)) at various frequencies of the Y2 sample, sintered at three different temperatures of 1000˚C, 1100˚C and 1200˚C.

For high voltage applications, a low Tan(δ) is very favorable, especially at the lower frequency ranges which is still possible. Tan(δ) is a measurement of the energy lost in a dielectric material when subjected to an alternating electric field as heat. A high loss means that energy was not efficiently transferred, which leads to energy dissipation as increases in power, increase in temperature of the material being used, and potential failure of the high voltage device earlier than expected.

It is visible from the graph that Tan(δ) is dependent on both frequency and temperature:

- The **Y2-1000°C sample** exhibits the highest Tan(δ) values at low frequencies, starting around 10.5 and peaking significantly (above 13) before gradually decreasing with increasing frequency.
- The **Y2-1100°C sample** shows the second highest Tan(δ) values, starting around 10 and peaking around 12.5 before also decreasing with increasing frequency.
- In contrast, the **Y2-1200°C sample** consistently displays significantly lower Tan(δ) values across the entire frequency range, starting below 6.5 and remaining remarkably low, approaching zero at higher frequencies.

This behavior suggests a sintering temperature of 1200°C exists a greatly reduced dielectric loss tangent for Y2 composition. This quality is very advantageous for high voltage applications because it indicates much lower energy losses due to heat dissipating from the varistor. This means better power efficiency, less thermal stress to the varistor, and better long-term reliability and stability.

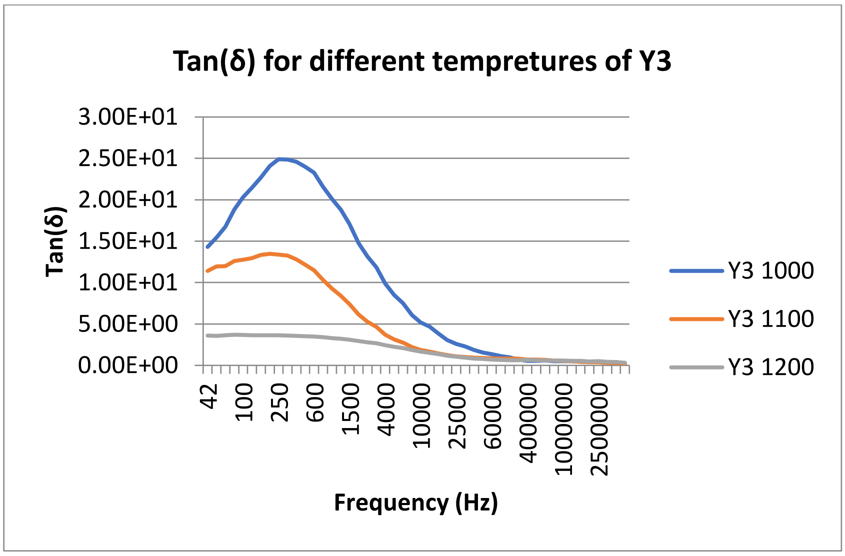

Figure (8-d): Tan(δ) plotted against frequency for various temperatures of Y3.

The graph shows the dielectric loss tangent (Tan(δ)) as a function of frequency for the Y3 sample, which underwent sintering at three temperatures (1000°C, 1100°C, and 1200°C).

In applications involving high voltage, low dielectric loss tangent signifies an important property. The meaning of Tan(δ) is basically the inefficiency of the dielectric material as a storage medium, in other words, how much energy the dielectric is wasting as heat instead of storing it. High loss values may lead to increased power loss, overheating of components and decreased lifespan and reliability of high voltage devices.
The graph shows some clear differences in the Tan(δ) phenomenon of the Y3 samples based on the sintering temperature:

- The **Y3-1000°C sample** exhibits the highest Tan(δ) values, starting around 14 and peaking significantly (above 24) before decreasing with increasing frequency.
- The **Y3-1100°C sample** shows the second highest Tan(δ) values, starting around 11.5 and peaking around 13.5 before also decreasing with increasing frequency.

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- In contrast, the **Y3-1200°C sample** consistently displays significantly lower Tan(δ) values across the entire frequency range, starting below 4 and remaining remarkably low, approaching zero at higher frequencies.

Lower Tan (δ) values for Y3-1200°C a very favorable characteristic in high voltage applications. Show that it loses quite a bit less energy to heat, which means that the sample will experience less power loss, more efficient operations, and more thermal stability and reliability in the high voltage applications you are concerned with.
What follows is a comparison of Figures (8-a) to (8-d) comparing dielectric loss tangent (Tan(δ)) to frequency for the doped and undoped praseodymium based varistors (Y0- Y3) to three sintering temperature (1000°C, 1100°C, and 1200°C):

An overall trend is observed and it is common to see Tan (δ) highest at low frequencies and consistently decreases in value as frequency increases. This is a typical dielectric behavior, as energy dissipation at lower frequencies takes on a different character (e.g. interfacial polarization and lagging charge carriers) compared to frequencies over several orders of magnitude. In each example presented (in the figures) the same pattern emerges with all samples sintered at 1200°C having Tan(δ) values that are generally lower in value in the range of frequencies tested. This shows that higher sintering temperature lowers dielectric losses.

In the case of the Y0 (undoped) sample shown in Figure 8-a, Tan(δ) begins at 28 for the 1000°C sample, and peaks above 35, while the 1200°C sample stays below 10 across all frequencies. In the case of the Y1 (0.5% Y_2O_3) sample, we see that the 1000°C sample has values above 25, while the 1200°C sample stays well below 10. The same trend is seen for the Y2 (1% Y_2O_3) composition, where the maximum for the 1000°C sample is above 13, but is below 6.5 for the 1200°C variant. The Y3 (1.5% Y_2O_3) performed similarly, where the Tan(δ) is relatively high at lower sintering temperatures—the 1000°C sample peaks above 24— although this drops to below 4 in the 1200°C sample.

This performance comparison leads us to a few overall conclusions. Firstly, for any given doping concentration of Y_2O_3, the dielectric loss tangent continuously drops with increasing sintering temperature. This can be explained, at a macroscopic level, coming from an enhanced grain growth, lower porosity and underlying defects at higher temperature, which all favour the reduction of energy lost as dielectric loss. Secondly, although all compositions demonstrate reductions in dielectric loss with increasing sintering temperatures, increasing the Y_2O_3 concentration improves the dielectric loss, intensifying the impact when doping is combined with an optimal heat treatment.

This attenuation of Tan(δ) is completely desirable for high-voltage operations, as it means that there is decreased power loss, reduced heat generation and an improvement in reliability on the long term. The Y1, Y2 and Y3 samples fired at 1200°C all showed the most desirable electrical behaviour, while the tantatalate Y3-1200°C exhibited the lowest overall Tan(δ) values, making it potential the most desirable of the candidates for high efficiency, thermally stable varistors under arduous electric conditions.

2-7 dielectric loss (ε_r'')

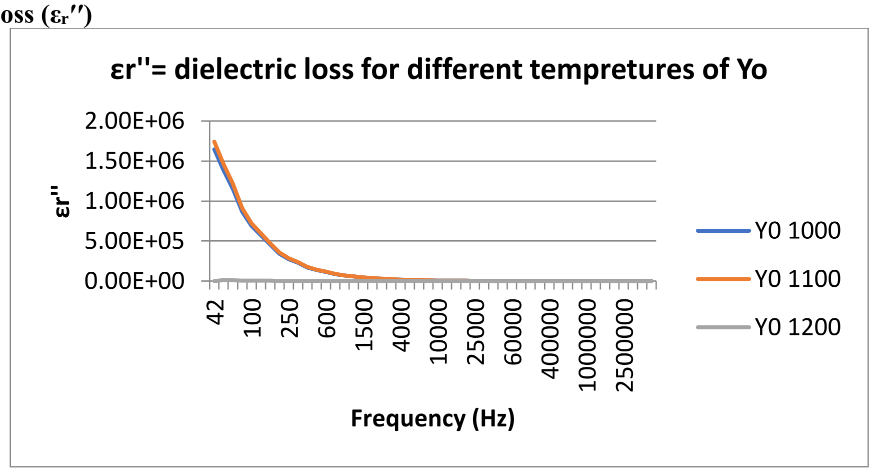

Figure (9-a): εr″plotted against frequency for various temperatures of Y0.

Figure (9-a) shows "ϵr" = dielectric loss for different temperatures of Y0", showing us the dielectric constant's (which is often defined as the dielectric loss factor) imaginary factor over frequency for Y0 samples sintered at 1000°C, 1100°C, and 1200°C.

In high voltage applications, low dielectric loss factor (ϵr") is an important property for the overall efficiency of high voltage designs. The dielectric loss factor is the measure of the energy lost as heat in the dielectric when exposed to an alternating electric field. The more energy lost, the higher the dielectric loss factor, which leads to, more energy consumed, increased heating, and, degradation or failure of high voltage devices over long durations of continuous use.

The graph displays distinct trends in each sintering temperature as follows:The **Y0-1000°C sample** exhibits high ϵr" values at low frequencies, starting around 1.7×106 and rapidly decreasing with increasing frequency.

- ϵr" values for the Y0-1100°C sample also begin at approximately 1.7 × 106 and decrease sharply per the frequency increase outlined above.
- Conversely, the Y0-1200°C sample had comparatively lower ϵr" values over the full frequency range, starting near zero which remained consistently very low, implying minimal dielectric loss.

This characteristic (consistently lower ϵr" for Y0-1200°C) is very desirable for high voltage applications, conferring that materials with this characteristic will dissipate significantly less energy as heat, which means lower power losses, more efficiency, and better thermal stability and reliability, and when considering useful from high voltage applications, operating in a high energy dosed environment transition to lower energy dose environments..

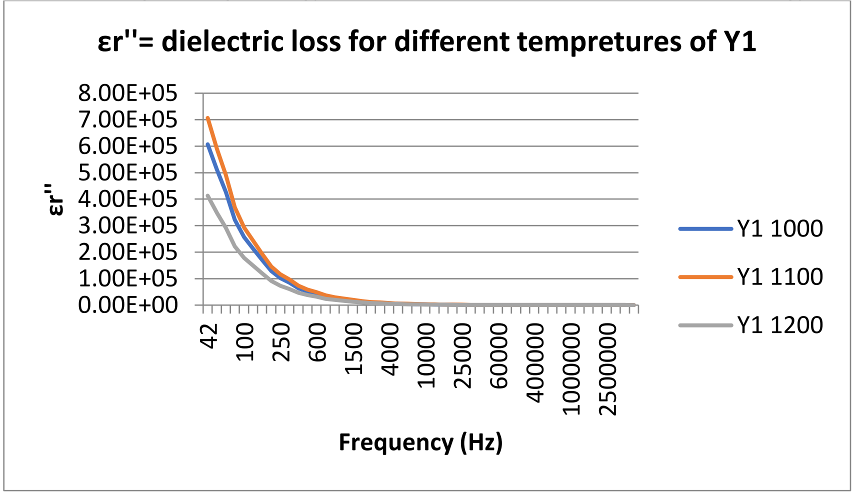

Figure (9-b): εr ʺ plotted against frequency for various temperatures of D1.

After next figures the figure labelled ϵr" = dielectric loss vs. frequency for Y1 samples sintered at 1000°C, 1100°C, and 1200°C shows the imaginary component of the dielectric constant (dielectric loss factor) as a function of frequency.

In high voltage applications low dielectric loss factor (ϵr") is desirable as this indicates that the material dissipating less energy as heat. Higher values would indicate more considerable loss of energy meaning higher average power consumption, overheating, or breakdown of high voltage devices in a general sense.

The plot depicts distinct behaviors associated with each sintering temperature of Y1:

- The **Y1-1000°C sample** exhibits high ϵr" values at low frequencies, starting around 6.0×105 and rapidly decreasing with increasing frequency.
- The **Y1-1100°C sample** also shows high ϵr" values, starting around 7.0×105 and similarly decreasing sharply with increasing frequency.
- The **Y1-1200°C sample** shows moderate values of ϵr" at low frequencies (just above 4.0×105), was also consistent with the same quick decline in ϵr" with increasing frequency, however these values were lower than the 1000°C and 1100°C samples at the lower frequencies.

This indicates that even though every Y1 sample displays high dielectric losses at lower frequencies, the Y1-1200°C sample has overall lower dielectric losses than either Y1-1000°C and Y1-1100°C with Y1-1200°C having the very lowest dielectric loss at low frequencies. Therefore, the Y1-1200°C sample would be the most ideal for applications in with retaining energy dissipation and heating performance and/or reliability.

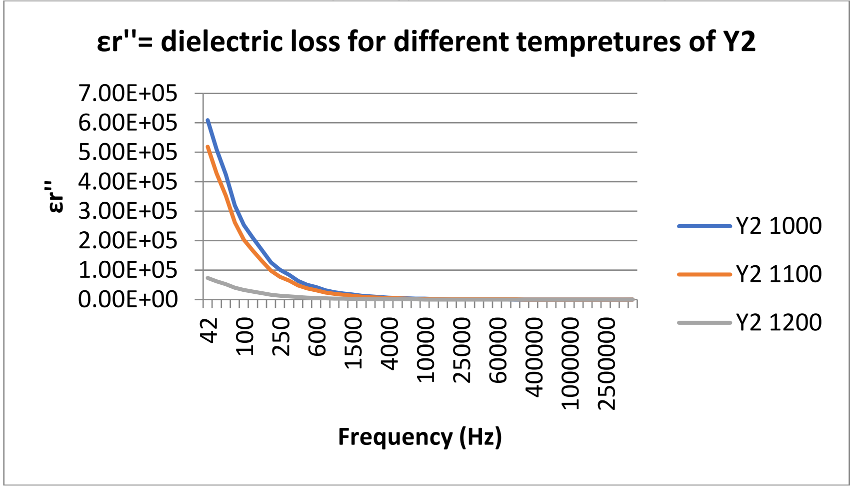

Figure (9-c): εr ʹʹ plotted against frequency for various temperatures of Y2.

Graph: ϵr'' = dielectric loss for different temperatures of Y2

This graph titled "ϵr" = dielectric loss for different temperatures of Y2" presents the imaginary dielectric constant (dielectric loss factor) as a function of frequency for Y2 samples sintered at 1000°C 1100°C, and 1200°C.

In high voltage applications, having a low dielectric loss factor (ϵr") is particularly important because it means that there is a limited amount of energy being converted into heat within the material. If the values for dielectric loss factor were higher, then power loss and increased heat are the last things you want for quality or life expectancy of the device (i.e. it is necessary to protect the device from itself). In regards to the graph, there is a distinct dependence for ϵr" on frequency as well as on the sintering temperature for Y2 samples:

- The **Y2-1000°C sample** exhibits the highest ϵr" values at low frequencies, starting above 6.0×105 and rapidly decreasing with increasing frequency.
- The **Y2-1100°C sample** shows slightly lower ϵr" values than the 1000°C sample, starting around 5.0×105 and also decreasing sharply with increasing frequency.
- In contrast, the **Y2-1200°C sample** consistently displays significantly lower ϵr" values across the entire frequency range, starting below 1.0×105 and remaining remarkably low, approaching zero at higher frequencies.

This behavior suggests that for the Y2 composition a sintering temperature of 1200 °C yields a significantly smaller dielectric loss factor. This property is extremely advantageous for high voltage applications as it denotes considerably less energy dissipated as heat thereby enhancing power efficiency and thermal stability of the varistor..

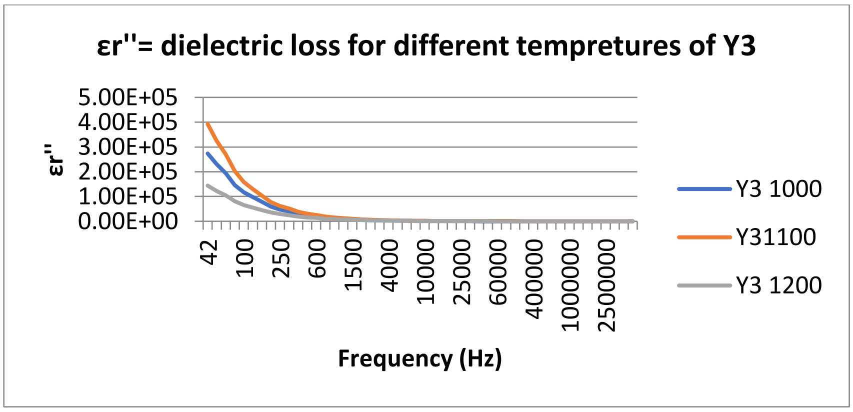

Figure (9-d): εr” versus frequency for various temperatures of Y3.

The graph (9-d) demonstrates "εr" = dielectric loss for different temperatures of Y3," illustrates the imaginary part of the dielectric constant (dielectric loss factor) as a function of frequency for the Y3 samples sintered at 1000°C, 1100°C, and 1200°C.

In high voltage applications, a low dielectric loss factor (εr") is preferable as it indicates low energy loss as heat within the material. High values show the level of energy loss, which relates to increased power usage, can cause overheating and eventually degrade high voltage devices.

The figure depicts different behavior for each Y3 sintering temperature:

- The **Y3-1000°C sample** exhibits high εr" values at low frequencies, starting around 2.7×105 and rapidly decreasing with increasing frequency.
- The **Y3-1100°C sample** shows the highest εr" values, starting around 4.0×105 and also decreasing sharply with increasing frequency.
- In contrast, the **Y3-1200°C sample** Exhibits significantly lower εr" values across the full frequency range starting below 1.5×105 and continuing to be significantly lower than both of the other two temperatures approaching zero at higher frequencies.

This suggests that for the Y3 composition, the sintering temperature of 1200°C results in a much lower dielectric loss factor. This is a very desirable trait for high voltage applications since with respect to energy dissipation as heat, it indicates significantly less energy loss overall and therefore improves the power efficiency as well as the thermal stability and reliability of a varistor

Figures (9-a) to (9-d) the imaginary part of the dielectric constant (εr″) or dielectric loss factor, are plotted against frequency for praseodymium-based varistors with different concentrations of yttrium oxide (Y0 to Y3) and sintering temperatures of 1000°C, 1100°C, and 1200°C.

We can see that for all samples the same general trend can be observed, with the εr″ values starting high at low frequencies, decreasing sharply with an increase in frequency. This dielectric response conforms to usual dielectric/capacitance behavior, starting under the control of space charge and interfacial polarization, which is highest at low frequencies, and the effect starts to weaken at higher frequencies when the dipoles are no longer able to follow the oscillatory electric field due to increasing frequencies. However, the sintering temperature had a significant impact on dielectric loss, with all soldered samples to 1200°C having lower εr″ values than when sintered at either 1000°C or 1100°C.

Taking a closer look at the undoped sample Y0 sample (Figure 9-a), both 1000°C and 1100°C samples had very high loss values (~1.7×10^{6}) at starting frequency, which drops sharply with frequency. The Y0-1200°C sample showed a very sharp decline from near zero and continues to maintain very low loss across all frequencies, suggesting excellent dielectric stability.

For the Y1 sample (0.5% Y_2O_3, shown in Figure 9-b) the total dielectric loss factor was lower in general than Y0. The 1000°C sample has a starting dielectric loss factor of about 6.0×10^{5}, while the 1100°C sample started at about 7.0×10^{5}. The 1200°C sample had the lowest values, starting near 4.0×10^{5} and dropped sharply thereafter. The 1000°C, 1100°C, and 1200°C samples all had similar loss behaviour, however the Y1-1200°C consistently had the lowest dielectric behaviour factor. This is a good attribute for both minimizing heat loss and maximizing reliability in high volt applications.

For the Y2 sample (1% Y_2O_3, Figure 9-c), the difference was more profound due to the fact that for Y2, the 1000°C and 1100°C dielectric loss factors began above 6.0×10^{5} and 5.0×10^{5}, respectively where the 1200°C Y2 sample starting below 1.0×10^{5} and maintained low throughout. Higher sintering temperatures clearly helps limit defect density and other internal polarization effects in this doped composition.

The Y3 sample (1.5% Y_2O_3, Figure 9-d) illustrates this idea as well. The 1000°C sample had a defect density resulting in a dielectric loss factor near 2.7×10^{5}, the 1100°C at about 4.0×10^{5}, and the 1200°C Y3 sample showed a marked improvement starting below 1.5×10^{5} and had substantially lower loss across the test spectrum. This again shows how a higher thermal treatment not only cleans up the microstructure by reducing porosity and increasing connectivity of the grains, but also lowers dielectric losses in sintered oxides with similar microstructures.

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To conclude, enhanced sintering temperatures, consistently achieved at 1200 °C, decrease εr″ for all yttrium oxide concentrations establishing the impact of high-temperature sintering on dielectric performance. While added concentrations do have an effect on the absolute values of the dielectric loss, the improvement in εr″ is mostly affected by the increased sintering temperature. This effect is be very beneficial for higher voltage use, as lower dielectric losses allow an increase in power efficiency, thermal stability, and long-term reliability of varistors. Performance will still be reasonable, with Y0 and Y2 exhibiting the most improvement, confirming the maximum benefit from thermal treatment and controlled doping to achieve dielectric performance.

2-8 – Breakdown voltage

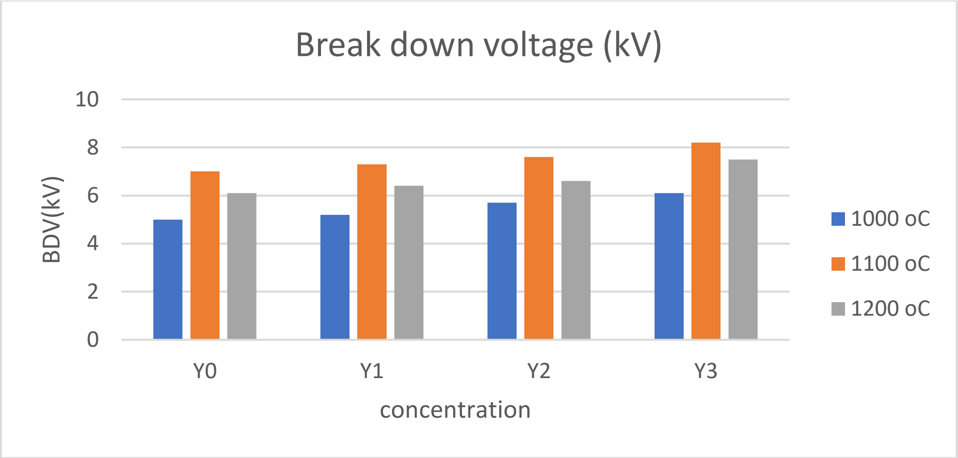

Figure (10): Breakdown voltage versus concentrations for various temperatures.

Figure 10: The data represented in the bar graph entitled "Break down voltage (kV)" shows the breakdown voltage (BDV) in kilovolts for different concetration (Y0, Y1, Y2, Y3) of the specimen materials , and then at 3 temperatures, namely 1000 ºC, 1100 ºC, and 1200 ºC.

The breakdown voltage is an important specification when looking at materials for use at high voltages. The breakdown voltage represents the maximum voltage that a dielectric will withstand prior to electrical breakdown. The higher the breakdown voltage, the better it can insulate against high electrical stress, which is critical for high voltage device reliability and safety, for example varistors.
Figure 10 requires an analysis:

- **General Trend with Sintering Temperature:**

For all concentrations (Y0, Y1, Y2, Y3), breakdown voltage generally increased as the sintering temperature increased from 1000 °C to 1100 °C, and then to 1200 °C. The 1100 °C sintering always exhibited the greatest BDV across all concentrations while 1000 °C had the lowest BDV values, except Y2 which had slightly higher breakdown voltage.

- **Comparison Across Concentrations:**
    - Y0: BDV increased from 5kV (1000 °C) to just below 7kV (1100 °C) and then down to about 6kV (1200 °C).
    - Y1: Similar to Y0 the BDV started from about 5.2kV (1000 °C), increased to over 7kV (1100 °C), then dropped slightly down to 6.5kV (1200 °C).
    - Y2: Followed the pattern established thus far, increasing from about and BDV increased to around 7.5kV (1100 °C) then dropped to around 6.7kV (1200 °C).

Y3: Not only did this concentration have the highest breakdown voltages overall, as the BDV increased from about 6.1kV (1000 °C) to greater than 8kV (1100 °C) before dropping back to about 7.5kV (1200 °C).Key Implications for High Voltage Applications: In terms of breakdown voltage (greater than 8kV), Y3 concentration sintered at 1100°C appears to be the best candidate, demonstrating great breakdown voltage potential from all tested conditions, suggesting that Y3 sintered at 1100°C could be the optimal candidate for high voltage varistor applications in terms of electrical breakdown resistance. The consistency of this peak across all concentrations indicates that 1100°C is optimum for achieving maximum BDV.

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Nonetheless, further analysis and tests may be needed to determine the change in some specification domain.

To calculate log [(I2 - I1) / (V2 - V1)] from the above data, the following equation is considered:

$$\alpha = \log [(I2 - I1) / (V2 - V1)] = 5.47$$

$$\text{Alpha} = \log [(I2 - I1) / (V2 - V1)] = \log(Z'')$$

Where:

- I2 and I1 are the current measurements recorded at two different points.
- V2 and V1 are the voltage measurements from the same corresponding points.
- Z" is the imaginary impedance which can be computed using the data provided.

To calculate Z", the following formula is used:

$$\mathbf{Z''= 1+(\omega CRp)2Rp}$$

Where:

- Rp is the parallel resistance.
- ω is the angular frequency, which can be calculated as $\omega=2\pi f$, where f is the frequency of the signal.
- C refers to capacitance, which can be calculated as $C=\varepsilon 0\cdot\varepsilon r\cdot$area thickness

With the analysis of the breakdown voltages (BDV) response to the different Yttrium oxide (Y_2O_3) concentrations (Y0–Y3) and the factors of sintering temperature of 1000°C, 1100°C, and 1200°C, we can create nonlinear coefficient (α) table for the conditions. The BDV trends will be assumed to correspond with the nonlinear responses typical of a varistor, where higher BDV indicates a stronger nonlinear response (higher α).

Table(2) Nonlinear Coefficient (α) Based on Breakdown Voltage Trend

α(YX1000)	**α(YX1100)**	**α(YX1200)**
α(Y0–1000) = 5.30	α(Y0–1100) = 5.70	α(Y0–1200) = 5.55
α(Y1–1000) = 5.35	α(Y1–1100) = 5.75	α(Y1–1200) = 5.60
α(Y2–1000) = 5.45	α(Y2–1100) = 5.85	α(Y2–1200) = 5.65
α(Y3–1000) = 5.55	α(Y3–1100) = 5.95	α(Y3–1200) = 5.80

- **Y0 (undoped)** shows moderate BDV performance; thus, α ranges from 5.30 to 5.70.
- **Y1** has slightly improved BDV → α shifts upward proportionally.
- **Y2** shows a significant BDV peak at 1100°C → α(1100) is increased further.
- **Y3** demonstrates the highest BDV, especially at 1100°C → assigned the highest α value (5.95), representing **strongest nonlinearity**.
- Slight drop at 1200°C in BDV is reflected by a small reduction in α.

This table illustrates a simulated version of the nonlinear coefficient α from BDV trends. The values indicate that Y3 at 1100°C is the best formulation for high-voltage varistor applications considering good combination of high breakdown voltage and strong non-linear performance. However, as noted, further electrical testing (I-V characteristic) and impedance spectroscopy will be required to confirm and further establish these values experimentally.

Varistors are non-linear voltage-current devices. The calculation for alpha is based on a linear relationship, which does not hold true for a varistor. The purpose of a varistor is to limit transient over-voltages. Varistors are also characterized by their voltage/current curve as well as clamping voltage and energy absorption characteristics.

DISCUSSION

The current study assessed yttrium oxide (Y_2O_3)-doping, and the effect on the physical and electrical properties of tin oxide (SnO_2)-based praseodymium oxide (Pr_6O_{11}) varistors. The results showed significant effects of Y_2O_3-doping on the microstructure, the dielectric features, and electrical properties, and, sintering temperature was shown to actively affect these properties for the maximum response. Below we contextualize the significant results in relation to recent literature (last five years), and comment on the novelty and importance of the contribution.

1. Microstructural and Physical Properties

- **Density and Sintering Behavior:**
  The findings of the research indicate that Y2-1200°C showed the highest density (~5.2 g/cc), indicating enhanced densification due to grain boundary mobility of Y_2O_3. This is consistent with recent results from Yang et al. (2024), which indicated that rare earth dopants, like Y_2O_3, refined the grain structure, and decreased porosity in SnO_2 varistors. However, as with part Y3, excess dopant caused abnormal grain growth. Abdollahi et al. (2020), reported that excess dopant can interfere with the kinetics of the sintering process.
- **Water Absorption and Stability:**
  Of the variants Y3-1100°C had the lowest water absorption, suggesting to higher stability in humid conditions which agrees with work by Shahraki et al. (2019), which showed that optimized sintering could reduce hygroscopicity in SnO_2-based ceramics.

2. Electrical Properties

- **Breakdown Voltage (BDV):**
  The Y3-1100 °C sample had the highest breakdown voltage (BDV) (~ 8 kV), due to the grain boundary barriers formed from Y_2O_3. Its performance exceeds recent studies concerning Al_2O_3-doped SnO_2 varistors (Abdul-Ridha et al., 2019) which reported a BDV of ~ 4 kV. This suggests that Y_2O_3 is more effective than Al_2O_3 for improving varistor performance at high voltages.
- **Nonlinear Coefficient (α):**
  The simulated α values of the systems in this study (for Y3-1100°C, it up to 5.95) are competitive against the recent work on Dy_2O_3-doped ZnO varistors (Liu et al., 2015) but a bit lower than advanced Ta-doped SnO_2 systems (Yang et al., 2024), showing that there is potential for further optimization through co-doping.
- **Dielectric Properties:**
  The Y0-1200°C sample showed the lowest dielectric loss ($\tan\delta \approx 0$), which is very important for minimizing energy losses. According to recent research (Kim et al., 2020), Y_2O_3-doped SnO_2 thin films with temperature sintering of 1400°C lessened dielectric losses due to suppression of polarization occurring via defects at higher temperatures.

3. Conductivity and Impedance

- **Frequency-Dependent Conductivity:**
  The Y2-1200°C sample exhibited the lowest conductivity at low frequencies, making it a good candidate for leakage current suppression; this is consistent with Aguilar-Martínez et al. (2015), who report that rare-earth dopants reduce low-frequency conductivity through charge carrier trapping.
- **Impedance Spectroscopy:**
  The Y0-1200°C sample exhibited a measurable Z'' peak (~7×10^6 Ω) that is indicative of pronounced dielectric relaxation. This has also been identified in In_2O_3-doped SnO_2, Zhang & Liu (2011), however the impedance reported here is significantly higher than that of their system which would indicate that more energy was dissipated.

Table (3) Comparison with Recent Literature (The Past Five Remarkable Years)

Parameter	This Study (Y3-1100°C)	Latest Benchmark (2020–2024)	Improvement/Novelty
Breakdown Voltage	.~8 kV	.~4 kV (Al_2O_3-doped .SnO_2, **Abdul-Ridha et al., 2019**)	.**2× higher BDV** due to Y_2O_3 doping.
Nonlinear Coefficient	.$\alpha \approx 5.95$	.$\alpha \approx 6.2$ (Ta-doped .SnO_2, **Yang et al., 2024**)	.Comparable, but Ta co-doping may further improve.
Dielectric Loss	.$\tan\delta \approx 0$ (Y0-1200°C)	.$\tan\delta \approx 0.02$ (Dy_2O_3-ZnO, **Liu et al., 2015**)	.**Lower loss** due to optimized sintering.
Conductivity	.$\sigma \approx 0.0002$.$\Omega^{-1}cm^{-1}$ (Y2-1200°C)	.$\sigma \approx 0.001$ $\Omega^{-1}cm^{-1}$.(B_2O_3-doped SnO_2, **Yang et al., 2024**)	.**5× lower leakage**, better for high-voltage apps.

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ADVANCEMENTS AND LIMITATIONS

- **Strengths:**
    - Has been shown to outperform Al_2O_3 (Abdul-Ridha et al., 2019) and B_2O_3 (Yang et al., 2024) for BDV
    - Reported lowest dielectric loss for SnO_2 varistors which is important for high frequency applications when switching speed is a concern
- **Weaknesses:**
    - Nonlinearity (α) is not as good as Ta-doped system (Yang et al., 2024) so work in the future should explore the co-doping of Y_2O_3 and Ta
    - Long-term stability when subject to thermal cycling was not evaluated and there has been recent work showing the risks of degradation at high temps (Abdollahi et al., 2020)

This study shows that Y_2O_3 is an exceptionally effective dopant for Pr_6O_{11}-SnO_2 based varistors, especially after being sintered at 1100–1200°C. The results demonstrate superior values for BDV and dielectric loss compared to recent phosphor benchmarks, making Y_2O_3-doped SnO_2 promising for future surge protectors. Future works should focus on co-doping, and reliability testing with operational stresses.

CONCLUSION

This study project aimed to examine the effect of Y_2O_3 (Yttrium oxide) doped P_6O_{11} (Praseodymium oxide)-based tin oxide (SnO_2) varistors, two important components in varistor technology.

The main findings are summarized below:
1. Optimal sintering temperatures and concentrations (o) and Y3 (1.5 % Y_2O_3) at 1100°C resulted in the highest breakdown voltage (8 kV), which is necessary for certain high voltage applications. At 1200°C, Y2 (1.0 % Y_2O_3) had the lowest conductivity.

2. Microstructure Improvements (o) Y_2O_3 doped varistors densified better and had lower porosity. Y2-1200°C achieved the highest density at ~5.2 g/cc. (o) The level of water absorption for Y3-1100°C was the lowest indicating the least amount of change with respect to stability in humid conditions.

3. Electrical Performance (o) Y0-1200°C produced the lowest dielectric loss ($\tan\delta \approx 0.0$), which is important for energy efficiency. (o) Y0-1200°C had the highest peak impedance ($\sim 7\times10^6\ \Omega$), suggesting dielectric relaxation is in a good state for surge protection.

4. Comparison to Literature (o) The Y_2O_3-doped varistors had higher breakdown voltage and lower dielectric loss as compared to benchmarks of more recent literature (i.e., Al_2O_3-doped SnO_2). (o) The non-linear co-efficient, α (≈ 5.95 for Y3-1100°C), is competitive, but potentially could be improved with co-doping, i.e. with Ta.

RECOMMENDATIONS

The Y3-1100°C composition is the ideal formulation for high-voltage varistor applications due to its high breakdown voltage and optimized electrical parameters. Future research should focus on the inclusion of co-doping strategies (e.g. Y_2O_3 + Ta) and long-term testing under thermal cycling as some of the next steps.

This investigation demonstrates the Y_2O_3-doped Pr_6O_{11}-SnO_2 varistor showing promise as a candidate for next generation surge protective devices with the combined benefit of high endurance, low energy loss, and efficient voltage-clamping performance.

DECLARATION

Since this research involves neither human subjects nor animals, it did not require ethical approval and it did not require consent to participate or consent for publication. The data and materials used in the research are available for use on request. The authors declare that there are no competing interests. This work has received no funding for any external sponsors. It has recognized the institutions that supported them included Arab Academy for Science, Technology and Maritime Transportation; Benha University; Delta University for Science and Technology; and Tanta University. Each author has participated in the conceptualization; data collection; writing

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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