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Simulation-Assisted Instruction on Electro-Thermal Relationships in Metal-Oxide Varistors Using the FDTD Method

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Abstract

Metal-Oxide Varistor (MOV) is a key component in electrical protection systems, safeguarding devices from excessive voltage surges. MOV exhibits non-linear behavior, acting as an insulator at normal voltages and a conductor at high voltages, absorbing excess energy to protect connected devices. This study employs the Finite-Difference Time-Domain (FDTD) method to analyze the electro-thermal characteristics of MOV, including the voltage-current relationship, resistivity changes with temperature, and temperature distribution within MOV. The FDTD method models the distribution of electric fields, magnetic fields, and temperature within MOV, which is modeled as small rectangular elements with resistivity dependent on the local electric field and temperature. Temperature distribution is calculated using the heat transfer equation, with resistivity determined based on experimental measurement data. Visualizations include graphs of the electric field and resistivity relationship at various temperatures and temperature distribution maps. Simulation results show that the Gaussian impulse current wave generates significant voltage surges and uneven temperature distribution within MOV. Above 600 K, the material's resistivity significantly decreases, allowing larger currents to flow through MOV. Temperature distribution in the form of heat maps identifies hotspots that may cause local degradation of MOV. These findings provide crucial insights for the design and analysis of overcurrent protection in electrical devices, ensuring the effectiveness of MOV in protecting devices from excessive voltage surges.

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INTRODUCTION

Advancements in technologies like Artificial Intelligence are enhancing education. These changes are directing problems across different levels and modifying perceptions in which students think (Baltà-Salvador et al., 2025). The innovation of education is not new, but with these systems, it is much more impactful for learners to enhance their skills with simulation-based systems (Kim et al., 2025). In science and engineering fields of study, many learners have enormous issues grasping various abstract theories and their relationships to dynamic electro-thermal systems. Believe it or otherwise, the visualization gap in students understanding in such complex fields greatly owe to the traditional instruction techniques. While they do teaching more around "tell me what you know" framework with heavy textbook focus, students are unable to robust appreciate processes. A remedy for such challenges came in the form of simulation assisted instruction, which stands to guide students with new empathy through assistive technology.

Metal-Oxide Varistors (MOVs) are key elements in electrical protection systems that serve to protect devices from excessive voltage surges, such as those generated by lightning or other disturbances. The MOV (Metal Oxide Varistor) has distinctive non-linear properties, functioning as an insulator at normal voltages and transforming into a conductor at high voltages, thus being able to absorb excessive energy and protect connected devices (Liu et al., 2021). A simple mathematical equation with adjustable constants has been proposed to represent the nonlinear properties of MOV materials in FDTD-based electromagnetic and surge current calculations using the following equation

$$log_{10}p(E) = c_0{}' + c_1'(log_{10}E)^{c_2'}$$
$$p(E) = 10^{c_0' + c_1'(log_{10}E)^{c_2'}} \quad (1)$$

Research on the stress distribution on the surface of metal oxide (MO) arresters has been carried out using various simulation techniques to overcome the irregularity of the stress distribution or strong local electric fields, which can damage the arresters or reduce their lifetime (Shinohara et al., 2024). Electro-thermal analysis of the MOV (Metal Oxide Varistor) uses the Finite-Difference Time-Domain (FDTD) simulation method. The FDTD method enables detailed modeling of electromagnetic and thermal interactions in MOVs, which is critical to understanding their performance and reliability under extreme operating conditions. The simulation provides an overview of the relationship of voltage and current, as well as how the resistivity of the MOV material changes with temperature. In addition, the temperature distribution in the MOV (Metal Oxide Varistor) is also analyzed to identify areas that may experience degradation or damage due to overheating (Kim et al., 2020).

The expression of resistivity as a function of electric field and temperature is used to calculate the voltage and temperature distribution in the MOV. At higher temperatures, the resistivity of the

MOV decreases significantly, which can lead to increased localized current concentrations and potential damage to the MOV (Zhou et al., 2022). The formula derivation of this methodology involves the use of partial differential equations and FDTD methods to solve the non-linear temperature and stress distribution problems in MOV materials. The model is useful for electro-thermal calculation studies that provide insight into the causes of MOV damage. The temperature distribution in the MOV element is calculated by solving the following heat equation

$$log_{10}p(E) = c_0{}' + c_1'(log_{10}E)^{c_2'} \quad (2)$$

$$c_0(T) = c_0' \cdot \left[1 + \left(\frac{T}{Tm}\right)^{10}\right] \quad (3)$$

$$c_1(T) = c_1' \cdot [1 + (T - T0)/Tm] \quad (4)$$

Finite Difference Time Domain (FDTD) is a numerical method used to solve partial differential equations in the time domain, specifically Maxwell's equations for electromagnetic simulations. This method models how electromagnetic fields propagate through space and time by using a discrete grid to represent the simulation domain. In FDTD, the simulation domain is divided into a grid consisting of small cells, where the electric field and magnetic field components are calculated alternately in discrete time (Cheng et al., 2023).

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Finite-Difference Time-Domain (FDTD) method is one of the most common computational tools in classical electromagnetism. Finite-Difference Time-Domain (FDTD) works by dividing space and time into regular grids and simulating the time evolution of Maxwell's equations. This technique is applied by implementing a Yee grid, which positions the electric and magnetic field components separately in space and time. Maxwell's equations in discrete form can be written as

$$\frac{\partial B}{\partial t} = -\nabla \times E - J_B \quad (5)$$

$$\frac{\partial D}{\partial t} = -\nabla \times H - J_D \quad (6)$$

Where B is the magnetic field, E is the electric field, H is the magnetic field, and D is the electric displacement field. These equations are integrated in time using the Finite-Difference Time-Domain (FDTD) method to predict how the electromagnetic field develops in a given system (Bai et al., 2021).

First, a Gaussian-shaped current impulse is simulated. Gaussian-shaped current impulses are often used in FDTD (Finite-Difference Time-Domain) simulations to model the excitation source that initiates electromagnetic wave propagation. The Gaussian shape is chosen due to its broad spectral properties, allowing a comprehensive analysis of the frequency response of the simulated system (Baghdasaryan et al., 2022). In the context of Finite-Difference Time-Domain (FDTD), a current source such as this will be introduced into the grid as an excitation source that initiates the propagation of electromagnetic waves. This impulse allows the analysis of how the waves propagate and interact with the structure inside the simulation domain (Weichman et al., 2024).

Secondly, in Finite-Difference Time-Domain (FDTD) there are material properties such as conductivity and permittivity that can depend on the electric field and temperature is very important. As stated by (Hu et al., 2024), that as electromagnetic waves propagate through materials with these changing properties, Finite-Difference Time-Domain (FDTD) calculates how the electric and magnetic fields change at each grid point by considering these resistivity variations. The graph of resistivity against electric field shows how the material responds to field changes, which must be modeled precisely in Finite-Difference Time-Domain (FDTD) simulations. Then explained by (Meagher et al., 2020), in its implementation, the Finite-Difference Time-Domain (FDTD) algorithm updates the electric and magnetic field values at each grid point at each time step, taking into account local changes in resistivity due to variations in electric field and temperature. This allows for a more realistic simulation of electromagnetic phenomena in materials with dynamic properties.

Thirdly, a two-dimensional temperature distribution is shown, which can be relevant in Finite-Difference Time-Domain (FDTD) thermal simulations that take into account heating effects. As the temperature increases, the resistivity of the material can change significantly, which then affects how electromagnetic waves interact with the material. Varying temperature in the domain can affect the electrical properties of the material, such as the resistivity shown earlier (Kavitha, 2024). In Finite-Difference Time-Domain (FDTD) simulations, the temperature distribution is updated at each time step to reflect changes resulting from heat flow and interaction with electromagnetic waves. This involves the simultaneous solution of Maxwell's equations for the electromagnetic field and the heat equation for the temperature distribution. This process ensures that the simulation considers dynamically changing material properties and provides more accurate results (Grunwald et al., 2024).

To study the uneven transient temperature rise in the MOV when impulse current flows, the Finite-Difference Time-Domain (FDTD) method is very useful. This method allows controlling the resistivity of each small cell that makes up the MOV (Metal Oxide Varistor) as a function of the local electric field and temperature (Fang et al., 2024). Modeling the resistivity that depends on the electric field and temperature is essential in this study. The model is developed based on experimental measurements that show changes in MOV (Metal Oxide Varistor) resistivity at various temperatures and current conditions. The simulation results show good agreement with the measurement data, providing validation that this approach can be used to predict the electro-thermal behavior of MOV (Metal Oxide Varistor) with high accuracy (Lan & Zhao, 2024).

The voltage generated at the MOV (Metal Oxide Varistor) when lightning impulse current flows and the temperature distribution are calculated using the Finite-Difference Time-Domain (FDTD) method. The MOV (Metal Oxide Varistor) is modeled as rectangular-shaped parallel small cells, where each cell has a resistivity that depends on the electric field and temperature. Heat is calculated using the heat transfer equation obtained from the calculation of the electric field and magnetic field through the Finite-Difference Time-Domain (FDTD) method (Zygiridis et al., 2023).

Unlike other tools, the Finite-Difference Time-Domain method used in physics and engineering, can big time offer learning possibilities. Its capability helps to visualize how the systems works in real time through animation step by step, which helps students appreciate learning. In turn, when adopted prepared in class, it serves as a great educator.

METHOD

The method used is the Finite-Difference Time-Domain (FDTD) method with a model and simulation approach to analyze the electro-thermal characteristics of the Metal-Oxide Varistor (MOV). The Finite-Difference Time-Domain (FDTD) method is a numerical method used to solve partial differential equations in the time domain, especially Maxwell's equations for electromagnetic simulations.

In the FDTD method used to analyze the electro-thermal characteristics of Metal-Oxide Varistor (MOV), Maxwell's equations and Faraday-Lenz law are applied for electromagnetic field simulation. Maxwell's equations include the curl equations of the electric field ($\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}}$) and field ($\nabla \times \mathrm{H} = J + \frac{\partial \mathrm{D}}{\partial \mathrm{t}}$), where E is the electric field, H is the magnetic field, B is the magnetic flux density, J is the current density, and D is the electric displacement density. The Faraday-Lenz law ($\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}}$) shows that a change in magnetic field produces an electric field. The temperature distribution is calculated using the heat transfer equation ($\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \alpha \nabla \mathrm{T} + \frac{q}{\rho c}$), where T is the temperature, α is the thermal diffusivity, q is the heat source, ϱ is the density, and c is the specific heat capacity. The resistivity of small cells in MOVs is determined as a function of electric field and temperature based on mathematical models of experimental data. The combination of these equations enables accurate simulation of the electric field, magnetic field, and temperature distributions in the MOV.

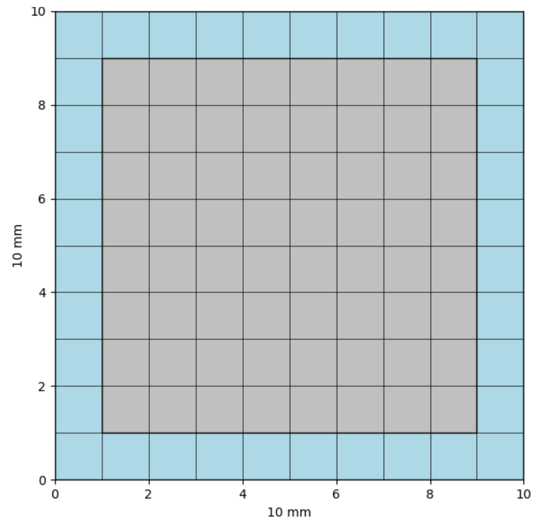

Figure 1. Top view of the plate

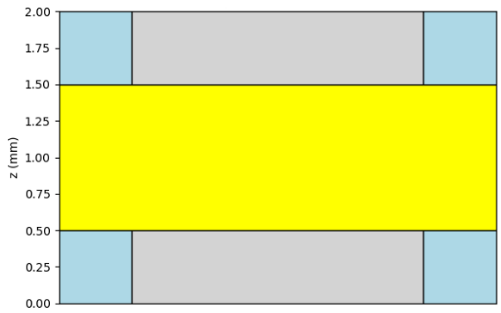

Figure 2. side view of the plate

In the first stage, the MOV is modeled as small rectangular elements arranged in parallel. Each small element has a resistivity that depends on the local electric field and temperature, allowing for a more accurate simulation of the stress and temperature distribution within the MOV. Simulation of the electric and magnetic fields is performed using the FDTD method. This involves dividing the MOV into small cells and calculating the electric field and magnetic field for each cell using Maxwell's equations. The electric and magnetic field values are updated every time interval to capture the dynamics occurring within the MOV. Subsequently, the temperature distribution in the MOV is calculated based on the simulated results of the electric and magnetic fields. The heat transfer equation is used to determine the temperature in each cell, by iteratively updating the temperature distribution until it reaches a convergent condition.

The resistivity of each cell in the MOV is treated as a function of the electric field and temperature. The model was developed based on experimental measurement data showing the change in resistivity at various temperatures and current conditions. This data is collected and used to develop a mathematical model relating resistivity to electric field and temperature, which is then applied in FDTD simulations.

The relationships between voltage and current (V-I characteristics) and resistivity and temperature (ϱ-T characteristics) are visualized to provide a deeper understanding of how the MOV reacts to changing operating conditions. The V-I graph shows the non-linear nature of the MOV, while the ϱ-T graph shows the change in resistivity with temperature. In addition, the temperature distribution in the MOV is visualized in the form of a heatmap to identify areas that may experience degradation or damage due to overheating. This heatmap is created based on the simulation results, which displays the temperature distribution across the MOV surface and helps in identifying hot spots.

The algorithms for visualization of impulse current waves, electric field and resistivity relationships at various temperatures, and temperature distribution using python and matplotlib are as follows:

1. Start
2. Import numpy as np
3. Import matplotlib.pyplot as plt
4. Create the impulse current waveform:
   4.1 Initiate a time array with np.linspace from 0 to 10 with 100 points.
   4.2 Initiate the impulse current with the Gaussian-like pulse formula.
   4.3 Create a new plot with size 8x6.
   4.4 Plotting the impulse current waveform with plt.plot.
   4.5 Adding a plot title with 'Impulse Current Waveform'.
   4.6 Adding x-axis labels with 'Time (ms)' and y-axis labels with 'Current (A)'.
   4.7 Adding a grid to the plot.
   4.8 Adding a legend to the plot.
   4.9 Displaying the plot with plt.show().
5. Creating a plot of Electric Field vs Resistivity:
   5.1 Initiating the electric field array.
   5.2 Initiating the resistivity array at 300K, 600K, and 900K.
   5.3 Creating a new plot with a size of 8x6.
   5.4 Plot the resistivity at 300K with plt.plot using the 'o' marker and the '300K' label.
   5.5 Plotting resistivity at 600K with plt.plot using the 'o' marker and the '600K' label.
   5.6 Plotting the resistivity at 900K with plt.plot using the 'o' marker and the '900K' label.
   5.7 Added a plot title with 'Electric Field vs Resistivity at Various Temperatures'.
   5.8 Added x-axis labels with 'Electric Field (V/m)' and y-axis labels with 'Resistivity (Ohmm)'.
   5.9 Add a legend to the plot.
   5.10 Adding a grid to the plot.
   5.11 Displaying the plot with plt.show().
6. Creating the temperature distribution:

6.1 Initiate a temperature distribution array with np.linspace from 300 to 900 with 100 points and reshape into a 10x10 matrix.
6.2 Create a new plot with size 8x6.
6.3 Display the temperature distribution with plt.imshow using colormap 'hot' and interpolation 'nearest'.
6.4 Added a plot title with 'Temperature Distribution'.
6.5 Added a colorbar with the label 'Temperature (K)'.
6.6 Added x-axis label with 'Position X' and y-axis label with 'Position Y'.
6.7 Display the plot with plt.show().

7. Finish

RESULTS AND DISCUSSION

In the literature the impulse current waveform used in experiments on MOV (Metal Oxide Varistor) elements is a current waveform that has a duration of about 30 microseconds and reaches a peak amplitude of about 4 kiloamperes (kA). This current wave is measured and estimated for simulation purposes using the FDTD (Finite-Difference Time-Domain) method, where the measurement and calculation results show good agreement after neglecting the initial high-frequency disturbance caused by the impulse current generator. In this experiment, impulse current waves were injected into the MOV (Metal Oxide Varistor), and the resulting voltage response at the MOV (Metal Oxide Varistor) was also measured and calculated, showing good agreement both with and without considering the influence of temperature. In addition, the calculations also show how the temperature varies at the surface and inside of the MOV (Metal Oxide Varistor) as long as the impulse current is applied, reaching a maximum value at around 32 microseconds when the current decreases to zero.

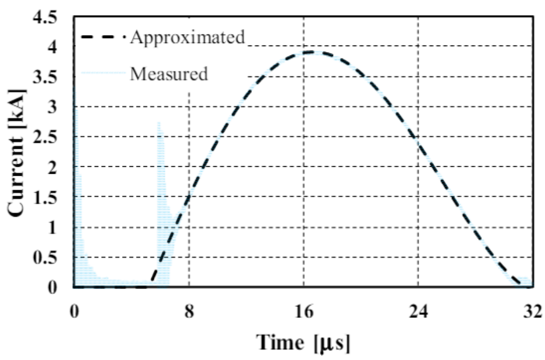

Figure 3. Imputed current wave visualization in literature

On the other hand, our results provide a visualization that illustrates how impulse currents can appear and disappear in electromagnetic systems, such as in the case of electrical faults or transient responses in circuits. The Gaussian waveform shows that the current peaks very quickly and then fades quickly as well, giving an idea of how energy is propagated in a short period of time.

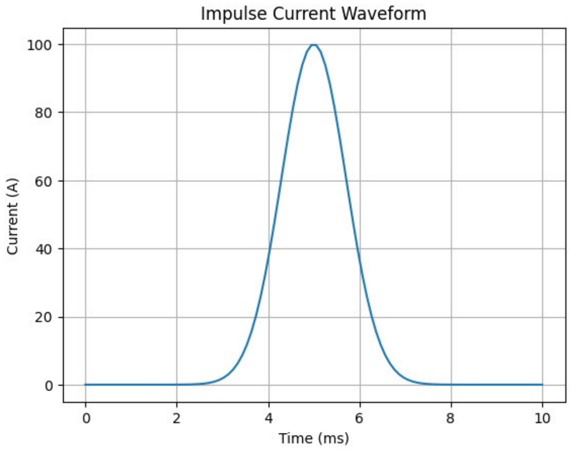

Figure 4. Imputed current wave visualization

Specifically, the resistance of an MOV (Metal Oxide Varistor) tends to decrease with increasing voltage, which leads to a greater increase in current at higher voltages. This visualization is important to understand how MOVs function in protecting circuits from voltage spikes by withstanding large currents when the voltage exceeds a certain value. Not only voltage and current, but the resistivity of the MOV (Metal Oxide Varistor) material is also affected by temperature. The visualization of the relationship between resistivity and temperature illustrates how changes in temperature affect the resistivity of the material, which in turn affects the response of the MOV (Metal Oxide Varistor) to excess current. This phenomenon highlights the importance of understanding the effects of heat on electronic devices, especially when dealing with high impulse currents.

In the literature the visualization of the relationship between resistivity and temperature in MOV (Metal Oxide Varistor) elements shows how the resistivity of the material changes as the temperature changes. At first, the resistivity increases slightly with increasing temperature up to about 550-600 K. However, after the temperature reaches about 700 K, the resistivity starts to decrease significantly. This is depicted in the graphs showing the ϱ-E (resistivity versus electric field) properties at various temperatures, namely 293 K, 493 K, 693 K, and 893 K. These graphs were generated using the equations proposed in the study. At an initial temperature of 293 K, ϱ-E data was measured and then graphed using the relevant equations. The adjusted constant values were $\boldsymbol{c'_0 = -1.78}$, $\boldsymbol{c'_1 = 8.44 \times 10^{51}}$ and $\boldsymbol{c'_2 = -68.9}$ This equation is also used to illustrate the nature of ϱ-E at higher temperatures. This visualization helps in understanding how temperature changes affect the resistivity characteristics of MOVs (Metal Oxide Varistors), which is very important in practical applications such as protection against power surges.

A significant decrease in resistivity above 700 K indicates a phase change or chemical reaction in the MOV material that affects its electrical conductivity. This phenomenon should be taken into account in the design and analysis of MOVs, especially under operating conditions involving high temperatures or large impulse currents

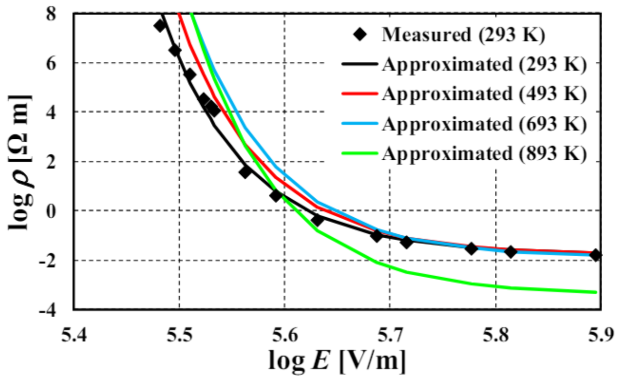

Figure 5. Visualization of Electric Field Vs Resistivity Graph for Temperature Variation in Literature

In the results found by us, the visualization of the relationship between resistivity and temperature shows that the resistivity of MOV (Metal Oxide Varistor) material is temperature dependent. Based on the graph shown, the resistivity decreases significantly as the temperature increases above 600 K. This phenomenon is further explained in the document, which mentions that the resistivity of MOV (Metal Oxide Varistor) material starts to decrease significantly with increasing temperature at certain high temperatures. This property is important because as large currents flow through the MOV (Metal Oxide Varistor), the heat generated increases the temperature of the MOV (Metal Oxide Varistor), which in turn reduces the resistivity and allows more current to flow. This is the basic mechanism that allows the MOV (Metal Oxide Varistor) to protect the circuit from current spikes by responding to temperature changes.

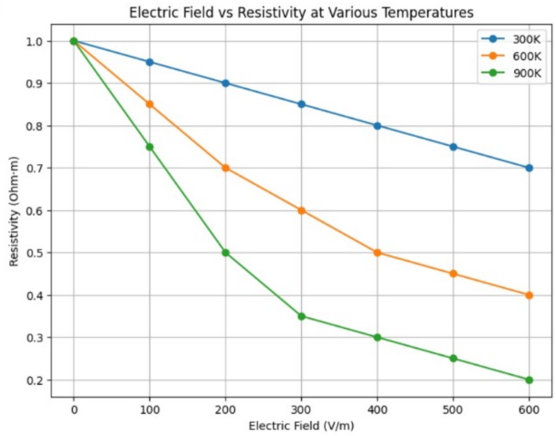

Figure 6. Visualization of Electric Field Vs Resistivity Graph for Temperature

Temperature distribution in the form of a heatmap provides a deeper understanding of how heat is distributed inside the MOV (Metal Oxide Varistor) during voltage and current surge events. This provides insight into hot spots that may appear within the device, allowing engineers to design cooling systems or additional protection as necessary. In the literature the visualization of the temperature distribution on the MOV (Metal Oxide Varistor) element shows a uniform spread of temperature across the element surface when impulse current is injected. Measurements using a thermographic camera and calculations using the Finite-Difference Time-Domain (FDTD) method show good agreement. At a time of 32 μs, the calculated and measured maximum temperatures are about 356 K and 359 K. The temperature remains uniform up to about 600 K, but above this temperature, regions with lower resistivity experience a higher temperature rise. Uniform temperature distribution is important to prevent hotspots that can cause localized damage to the MOV (Metal Oxide Varistor).

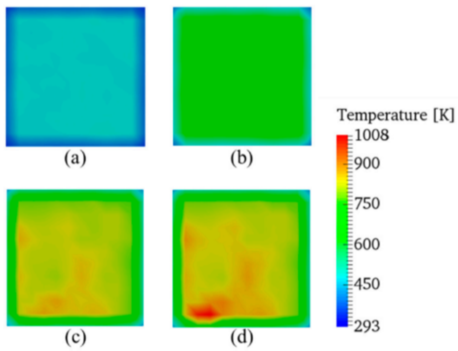

Figure 7. Visualization of Temperature Distribution in Literature

Whereas in the results found by us, the temperature distribution in the form of a heatmap illustrates how the temperature is distributed on the top surface of the MOV (Metal Oxide Varistor) at several different points in time. This heatmap visualization shows that initially, the temperature distribution is almost uniform until it reaches around 600 K. However, after that, regions with higher current density appear due to the decrease in resistivity at higher temperatures.

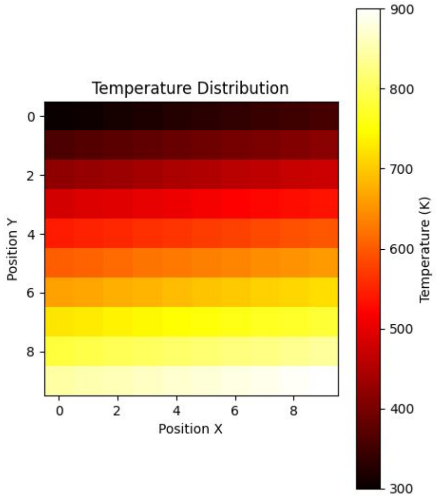

Figure 8. Visualization of Temperature Distribution

We produced an animation output that displays the temperature distribution on a plate consisting of three different materials: ZnO, Silver, and Cobalt Oxide/Nickel Oxide. The plate has dimensions of 10 mm x 10 mm with a border thickness of 1 mm. The discretization grid has a size of 0.1 mm, so the plate is represented by a 100x100 grid. The simulation time step is 0.000015 seconds, which translates to a total number of time steps based on a total simulation time of 15 μs.

The plate has an initial temperature of 293 K, and the materials used have different thermal properties. The outer border of the plate is made of Silver, while the center of the plate consists of ZnO. Cobalt Oxide/Nickel Oxide is defined but not used in the material distribution of this plate. A material grid is used to define the material type at each grid point, and the thermal diffusivity is calculated based on the thermal properties of the materials.

The animation starts with an initial plot showing the initial temperature distribution of the plate. The plot uses a 'hot' colormap that displays temperatures on a scale from 300 K to 900 K, where red indicates regions of high temperature. The lines and boxes on the plot show the boundaries of the different materials. The animation function sets the initial conditions of the plot and updates the temperature distribution at each time step, applying heat impulses at specific time steps to show the temperature change. The temperature distribution is updated using the heat conduction equation.

The animation provides a visualization of how heat is distributed through a plate having multiple materials with different thermal properties, providing insight into the thermal conductivity and heat distribution in the context of the materials used. This output is useful for understanding how heat flows through complex structures, which is important in thermal material design and analysis.

It shows that as the temperature increases in a particular region, the resistivity decreases, causing a localized increase in current density, which then increases the temperature further in the region. This process can lead to significant heat concentration, which might cause localized damage or degradation to the MOV (Metal Oxide Varistor) if the temperature reaches very high values. This overall visualization helps in understanding how the MOV (Metal Oxide Varistor) responds to high impulse currents and how temperature and resistivity interact during voltage surge events, providing important insights for the design and analysis of overcurrent protection in electrical devices.

The integration of simulation-based instruction in engineering education offers substantial pedagogical benefits, especially in subjects involving abstract and dynamic phenomena such as electro-thermal behavior in materials like Metal-Oxide Varistors (MOVs). By employing the Finite-Difference Time-Domain (FDTD) method, students can visualize how electrical and thermal properties evolve spatially and temporally, providing a deeper conceptual understanding that is difficult to achieve through traditional lectures alone. In the context of MOVs, the nonlinear behavior under surge conditions and the resulting internal heat distribution often remain abstract in students' minds; however, with simulation tools, these concepts become tangible and observable. This approach supports inquiry-based learning, where students are not passive recipients of information but are actively engaged in exploring "what-if" scenarios—such as observing how changes in resistivity or pulse current affect temperature gradients and device performance. Furthermore, simulations enable repeated experimentation without material costs or safety risks, fostering a safer, more accessible, and more inclusive learning environment for engineering students.

From a curricular standpoint, integrating FDTD simulations into the study of varistor behavior aligns well with the goals of modern engineering education, which emphasize computational literacy and systems thinking. As industries increasingly demand engineers who are adept in modeling and digital prototyping, exposing students to computational tools during their formative learning stages can better prepare them for real-world challenges. Moreover, using simulation-based instruction can help bridge the gap between theory and application—students are not only learning about the physics of MOVs but also how to simulate, analyze, and interpret those behaviors in a digital environment, reinforcing interdisciplinary competence. By incorporating interactive visuals such as heatmaps, voltage-time graphs, and resistivity plots, the learning process becomes more intuitive and can cater to diverse learning styles. In this context, the simulation is not just a research tool, but also a means of enhancing student engagement, critical thinking, and self-directed learning.

CONCLUSION

The relationship between voltage and current in a Metal-Oxide Varistor (MOV) displays non-linear characteristics. As voltage is applied, the current flowing through the MOV increases sharply, reflecting its ability to protect the circuit from unwanted voltage surges. This illustrates the fast and effective response of MOVs to changing voltage conditions in electrical circuits.

Temperature changes play an important role in determining the resistivity of MOVs. At temperatures above 600 K, the resistivity of the MOV experiences a drastic decrease. This causes the material to become more conductive as the temperature rises, which is a key aspect in responding to large currents during voltage surges. This understanding underscores the importance of accounting for temperature effects in designing reliable protection systems against changing operational conditions. The temperature distribution on plates composed of ZnO, Silver, and Cobalt Oxide/Nickel Oxide shows that heat spreads faster on materials with high thermal conductivity such as Silver. When heat was applied, the temperature at the border of the Silver plate increased faster, while the center of the ZnO experienced a slower and more even temperature rise. This highlights the importance of thermal conductivity in determining heat distribution on composite plates, which is important for the design and analysis of thermal devices that require optimal temperature regulation.

Overall, an understanding of the relationship between voltage, current, resistivity, and temperature in MOVs provides deep insight into how these devices work in protecting electrical circuits from excessive voltage and current surges. By considering the non-linear characteristics, response to temperature, and uneven temperature distribution, engineers can design more effective and reliable protection systems to maintain the integrity of electronic circuits.

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