Test method of pulse response characteristics for conductive switching materials induced by electromagnetic pulse field

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Abstract Electrical field induced conductive switching materials are novel nonlinear materials. They can show an abrupt reduction of resistivity when the external electrical field strength exceeds a predefined threshold, and the materials will switch from insulated state to conductive state. In this letter, a novel time-domain response characteristics test method of conductive switching materials induced by electromagnetic pulse field was proposed based on the parallel micro-strip principle. In the experiments, the test principle was analyzed by the equivalent circuit model and micro-strip principle, and the evaluation method of resistivity, response time and field strength threshold value of the materials under tested was also given. The theoretical results of the typical conductive switching material agree well with the experimental data.

key words: Conductive switching material, parallel micro–strip principle, response time, electromagnetic pulse

Classification: Electromagnetic theory

1. Introduction

The traditional electromagnetic protection materials, which are made up of metal, conductive composites, coating and shielding fabrics with invariant conductivity or permeability, are used for attenuating or eliminating electromagnetic interference and attack based on reflection, absorption and guidance of electromagnetic wave [1, 2, 3, 4, 5]. However, these sorts of materials cannot be applied for the protection of the electronic systems with transmitting and receiving functions of electromagnetic information. The novel conductive switching materials with nonlinear conductive characteristics (or called nonlinear I-V behavior) induced by electrical field within several nanoseconds have become a much-needed functional requirement. Here the material should be an insulator or highly-resistant within an allowable voltage range and become conductive or low-resistant when the applied voltage is larger than a predefined threshold, which is particular interested in the area of protection of electromagnetic pulse for electronic device [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. The test method of the electromagnetic pulse response characteristics for conductive switching material induced by electrical field is the key approach for evaluating the properties of these kinds of material. Previous studies mostly focused on Direct Current (DC) test method of material, which mainly revealed the relationship between current and direct voltage to obtain materials’ static performance parameters [16, 17, 18]. Four-probe technique, which is a typical DC test method, has been always used to measure the resistivity of material [19, 20], whereas it cannot endure high voltage and large current when the material conducted. For pulse measurement, free-space method and resonance method are mainly used to measure dielectric constant and magnetic permeability of material via vector network analyzer [21, 22]. Cable reflection method cannot measure the resistivity changing from the insulator state to conductor state under strong electromagnetic pulse due to its low operating voltage [23, 24]. In addition, for the measurement of response time, which is the delay time from high resistance to low resistance, China National standard GJB 911-90 only provides the test method of Electromagnetic pulse (EMP) protection devices under high voltage currently [25]. Owing to the difference in structure between the protection device and these kinds of material, the test method and test fixture can’t applied to the test of the material. G. Seo reported switching characteristics for VO₂ devices fabricated on silicon, and investigated the delay time and rising time of the metal–insulator transition (MIT) jump with varying low input voltage (about 1-2V) pulses and external resistance[26]. Yan Zhang proposed a simple resistance-capacitance thermal circuit model to explore the minimum switching time for thermally-driven two-terminal VO₂ devices [27]. J. Leroy demonstrated current-voltage characteristics of the VO₂-based two terminal devices, which showed a main abrupt MIT with pulse voltage threshold values of several volts [28]. These test method were mostly utilized by two terminal switching devices induced by low pulse-voltage based on measuring voltage on external resistance, whereas the conductive switching materials were used to protect electromagnetic pulse field with fast rise time (1-2ns) and

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DOI: 10.1587/exle.16.20190669
Received November 1, 2019
Accepted November 2, 2019
Publicized December 27, 2019

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strong pulse field (50kV/m), and currently how to observe the switching characteristic under high voltage without pulse distortion for these kinds of material has been seldom reported.

In this letter, we propose a new test fixture and test method for conductive switching materials induced by electromagnetic pulse field based on parallel micro-strip principle. A direct correlation between output voltage and on-state resistance is derived by micro-strip reflection theory, which describes the waveform quantitatively according to the equivalent circuit model of test system. Meanwhile, in order to prove the validity of the equivalent circuit model and equation of the output waveform in time domain, a pulse response time is clarified, and the switching characteristic of the tested material are measured practically.

2. Test fixture and modeling

For pulse measurement, as shown in Fig.1, the input pulse applied on the material was generated by a high voltage pulse generator called high frequency noise simulator Ins-4040 with 10V-4kV rectangular-shaped pulse, 50Ω output resistance, 1ns rise time and 50ns-1us pulse width, which has the characteristics of fast rise time, strong electromagnetic field, large current and wide spectrum. To ensure the output pulse measured by an Agilent oscilloscope 54845A through the test fixture without distortion, the test fixture (see design drawing in Fig.2) based on the 50Ω micro-strip as signal’s transmission line in the test circuit was designed. Adjusting the length and width of the micro-strip and the parameter of circuit board can satisfy the pulse without distortion at high frequency. The shell of the test fixture, which is made by aluminum, is used to fix the test circuit, thus had a common ground with the bottom of test circuit. Moreover, the shell can shield from the external interference. In the test circuit, Assume that the tested material is a resistance R, which is fixed by the two same bar-type electrodes welded on the micro-strip and ground respectively. Each electrode consists of a top electrode with screw hole, a bottom electrode with screw hole and two screws. The structure of electrodes were used to hold the tested material well and provide the uniform field in horizontal polarization, thus the material was in parallel with the micro-strip. Based on the equation of voltage and field (E=U/d), input voltage can reach 4kV, and the distance of the two parallel electrode(d) sets as 2mm, thus the two parallel electrode can provide the strong electromagnetic field (2×10^6 V/m) for the tested material. The transmission parameter S21 of test fixture measured by Vector Network Analyzer equals approximately 0dB within the frequency of 1GHz, and the reflection parameter S11 is less than -20dB, which proved the test fixture shows good transmission performance.

Before the tested material was held or the applied field was below the threshold value, the material shows insulating states with large resistance, which cannot play any role in the test circuit, and then the output waveform was same with the input one. However, when the enough strong field applied on the material, the insulating state converted to metallic, and the output waveform can generate great change in terms of magnitude, waveform shape and so on. Actually, we need to confirm exactly the switching characteristic of material according to the output waveform, such as the response time from insulating to metallic state and the resistance after transition (Ron), thus the equivalent circuit model of the test system was established (see Fig.3). As shown in Fig.3, V_s is internal DC charging power supply of Ins-4040, Rs is current-limiting resistance with MΩ level, and the cable marked in Fig.1 is a 50Ω output cable of pulse source with length as 20cm. When the switch is closed, it can produce a single rectangular-shaped pulse with the input voltage V_i.

![Fig.1 Test system, the left one is high frequency noise simulator Ins-4040, which can generate the rectangular pulse, the right one is the Agilent oscilloscope 54845A, the red circle denotes the test fixture.](image1)

![Fig.2 The design drawing of test fixture.](image2)

![Fig.3 Equivalent circuit model of the test system.](image3)

According to the reflection theory of transmission line, when the tested material shows low-resistance, the tested material acts as a load in parallel with the oscilloscope, thus the load impedance Z_l=R||Ro, We set R as 50Ω, therefore the test circuit cannot present the state of impedance match, and can produce the reflected wave from the load terminal firstly. The reflection factor is given by:
\[ \gamma_s = \frac{Z_1 - Z_o}{Z_1 + Z_o} \]  
\[ V_{i} = (1 + \gamma_s) \times V_0 = \frac{R}{Z_s + R} \times V_0 \]  
(1)  
(2)

Since the impedance of micro-strip \( Z_s \) is 50\( \Omega \), and the load impedance is always less than 50\( \Omega \), the reflection factor is negative in any condition. When there are reflected waves on the micro-strip, the terminal output voltage will be the superposition of incident and reflected waves, thus the first output voltage \( V_{i} \) on the load can be expressed by the following equation:

\[ V_{i} = (1 + \gamma_s) \times V_0 \]

When the first reflected wave reaches the pulse generator, due to its resistance \( R_s \) is much higher than \( Z_s \), thus the reflection factor of the pulse generator \( \gamma_s \) is approximately 1, and the total reflection on generator will be occurred. When this reflection returned to load, then the second reflected wave will be generated. The delay between the first reflected wave and the second one is the propagation delay time \( \tau_c \). Considering the influence of the pulse generator, \( \tau_s \) includes two parts: its internal cable delay and the output cable delay \( \tau \), the former one is the pulse width \( \tau_w \) of pulse source, the latter one can be calculated by \( \tau = \frac{1}{c} \sqrt{\frac{Z_s}{R_s}} \), \( l \) is the length of its output cable, \( \varepsilon_c \) is the relative permittivity of cable inner core, and \( c \) is the transmitted speed of electromagnetic wave. Therefore, after the propagation delay time \( \tau_c \), the second output voltage \( V_{i+1} \) on the load is as follows:

\[ V_{i+1} = \Gamma_{i} \times V_{i} \times (1 + \Gamma_{i}) \]

Similarly, \( V_{i+1}, V_{i+2}, \ldots V_{i+n} \) are also deduced in the same manner:

\[ V_{n} = \Gamma_{1} \times \Gamma_{2} \times \cdots \times (1 + \Gamma_{n}) \]

The polarity of output waveform alternates positive with negative, and \( |V_{n+1}| > |V_{n}| \). Finally, the relationship between \( V_{n} \), \( V \) and \( R \) is given in the time domain:

\[ V_{i+1}(t) = \sum \left[ \delta(t - \tau_s - \tau_c - l) \right] R \frac{Z_s}{Z_s + R} \left[ \delta(t - \tau_s - \tau_c) - \delta(t - \tau_s - \tau_c - l) \right] \]

Where \( \delta(t) \) denotes the jump function.

3. Results and discussions

In order to verify the effectiveness of equivalent circuit model and above equations obtained by reflection theory, several resistors were placed between the micro-strip and ground in test fixture to observe their output waveforms. Actually, different resistor shows different waveforms, some waveforms only have a positive pulse, and some waveforms have many positive and negative pulses, these pulses are all flat rectangular-shaped pulse. The values of pulse width \( \tau_w, V_{i0}, V_{i1}, V_{i2}, V_{i3} \) at the applied voltage of 10\( ^{3} \)V were recorded in Tab.1. Tab.1 shows that \( \tau_w \) of each pulse was constantly not change, and \( V_{i0}, V_{i1}, V_{i2}, V_{i3} \) varied with different resistance, while the sum of the absolute value of all the output voltage equaled the value of \( V \). With the increase of the resistance \( R \), reflection voltage \( V_{i0} \) increased gradually, and the number of positive and negative pulse reduced. The absolute value of \( V_{i0} \) presented normal distribution, and the maximum value was reached at the resistance of 25\( \Omega \). The \( V_{i1} \) reached the largest value of 130\( \Omega \) at 10\( \Omega \). Comparing \( V_{i0}, V_{i1}, V_{i2}, V_{i3} \) via measured by experiment and calculated by equation (4), the test result was perfectly matched with calculation except for the error of the pulse generator itself, which verified the correction of model and equation. Considering that \( V_{i0} \) is the largest one of all the reflection voltages for each resistor, test accuracy is also highest. In order to judge the test range of the test system correctly, the relation curve between \( V_{i0} \) and resistance \( R \) with measured by experiment and calculated by eq.2 is given in Fig.4. It can be seen from Fig.4 that the change of measured output voltage would not happen if the resistance exceeds 1k\( \Omega \), and when resistance is between 330\( \Omega \) and 1k\( \Omega \), the output voltage is approximately equal to the applied voltage, the difference between them is only several mV after the attenuation of 60dB. In addition, the total noise level of test system from the error of INS-4040 output pulse and attenuator and the bottom noise of oscilloscope are at mV orders of magnitude. Thus the test accuracy of test fixture mainly depends on the accuracy of oscilloscope and pulse source. However, when the resistance decreased below 330\( \Omega \), the test accuracy was greatly improved, and the output voltage waveform changed obviously when the resistance is below 50\( \Omega \). The resistance is littler, the test accuracy is higher. That is due to the resistance is paralleled with characteristic impedance \( Z_s \) of micro-strip. Therefore, when the resistance with the state of material changed was below 330\( \Omega \), the resistance change mechanism can be measured by this test system.

| R (\( \Omega \)) | Waveform Shape | \( \tau_w \) (\( \mu s \)) | \( V_{i0}(V) \) | \( V_{i1}(V) \) | \( V_{i2}(V) \) | \( V_{i3}(V) \) |
|-------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1.2\( \Omega \) | positive and negative | 1us | 45.8 | -37.5 | 33.3 | -29 |
| 5.1\( \Omega \) | positive and negative | 1us | 163 | -120 | 108 | -88 |
| 10\( \Omega \) | positive and negative | 1us | 280 | -185 | 130 | -101 |
| 25\( \Omega \) | positive and negative | 1us | 485 | -240 | 120 | -50 |
| 51\( \Omega \) | positive and negative | 1us | 665 | -220 | 62 | 0 |
| 100\( \Omega \) | positive and negative | 1us | 792 | -140 | 0 | 0 |
| 220\( \Omega \) | positive and negative | 1us | 870 | -90 | 0 | 0 |
| 330\( \Omega \) | positive and negative | 1us | 909 | -62 | 0 | 0 |
An electrical field-induced conductive switching material (modified graphene material [29]) was measured by the proposed test fixture (see Fig.1). The attenuation factor is 60dB. Fig.5 shows the output waveform after state change of the material under strong electromagnetic field. Here the output waveform is composed of positive and negative pulses ($V_{o1}$, $V_{o2}$ and $V_{o3}$), which is quite different from the original rectangular waveform. At a threshold voltage of 200V, positive voltage rises to a highest value, at the same time, the resistance of the material is decreasing abruptly. After several nanoseconds, the resistance of the material tends to be stable, thus the voltage decreases to a lower steady-state value, and formed the voltage overshoot, where the steady-state value is the output voltage $V_{o1}$. Since the output voltage continuously reflected, the $V_{o2}$ and $V_{o3}$ occurs, and propagation delay time $\tau$ among them were both 2ns. Here $\tau$ is calculated by real test system and it is negligible within 1us pulse width.

However, the modified graphene material we used here or other electrical field induced conductive switching materials are different from the fixed resistance, which the resistance of the material will recover to its original high resistance state in certain time after the applied pulse disappeared. In this case, the tested material gradually returned to the state of high resistance after about 2us. According to the above reflection theory, the reflection factor varied, thus the situation that $V_{o2}$ is bigger than the absolute of $V_{o1}$ happens. Therefore, before the tested material recovers to high-resistance or $n*t_w$ is less than the recovery time, the waveform shape excluding the voltage overshoot caused by the sharp change of resistance is consistent with the calculation result (see Eq.5) deduced by the equipment circuit model. According to the above verification experiment, with the decrease of $R$, the voltage $V_{o1}$ will become low, and the overshoot is more easily observed. By observing the steady-state value after the tested material state change, the $R_{on}$ is 6.25$\Omega$ that can be calculated by Eq.2. The off-state resistance (Roff) is $1.06 \times 10^6 \Omega$ tested by DC measurements. Therefore, the transition ratio (Roff/Ron) is roughly $1.7 \times 10^2$, and the threshold field is roughly 65kV/m. For response time of two-terminal VO$_2$ device, its definition has not a uniform standard. Y.zhou defined the response time as the time needed for the device resistance to change from Roff to Roff ($R_{on}$/Roff) 0.9, which is detected by device current density versus time curve [30]. Radu [31] presented the real time response waveform of the applied voltage and scope voltage showing that the response time at that applied voltage. These evaluation method of response time were different based on different test system and two-terminal device, but they were not contradictory, only the applicable condition were different, the former one was suitable for the condition that the response time is more than fast time of input pulse, the condition of the latter one was contrary to the former one. Therefore, when the output waveforms possess overshoot part, the definition of response time could refer to the former one. Here, we define the switching time from highest value to steady-state value as response time (see Fig.5). It can be seen from the Fig.5 that voltage decreased from 0.2V to 0.04V within 3ns, and the resistance of the material changed from $1.06 \times 10^5 \Omega$ to 6.25$\Omega$, so the response time of graphene modified material can be determined as 3ns.

In order to ensure the overshoot only be caused by transition of material, we replaced the copper with material, since the resistance of copper is close to zero, thus the output waveform was also flat. The above result has enough evidence to prove the rationality of the response time discussed above.

**4. Conclusion**

We have presented a circuit model that provides a phenomenological description of the voltage waveform with varied resistance, and also deduced the equation of...
output voltage in time domain. Several verification tests and material tests were implemented, which have proved the validity of the proposed method. The experiment results show that test fixture is suitable for those higher resistivity materials, whose on-state resistance is below 330Ω. When the on-state resistance is less than 51Ω, the output waveform will be occurred: the rectangular-shaped pulse of alternating positive with negative, and the resistance was determined by the steady-state value of the first positive pulse. In addition, response time mainly depends on voltage overshoot of the output waveform. Experiment results show that graphene modified material can repeat the on-off state transition, and the on/off ratio achieves 1.7×10^4, the response time is about 3ns. The test system and test method can be utilized by the parameter measurement for conductive switching materials induced by electromagnetic pulse field.

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