Fast Rise-Time Electromagnetic Pulse Protection Characteristics of ZnO Varistors

Wangwei Zhang [1], Yun Wang [2], and Junchao Shen [3]

[1] Academy of Software
Zhengzhou University of Light Industry, Zhengzhou, 450002, China
2018014@zzuli.edu.cn

[2] Department of science and technology of Henan Province
Zhengzhou, 450002, China
wangyunjunxie@163.com

[3] Henan University of Chinese Medicine, Zhengzhou, 450002, China
sjcwyyx2018@163.com

Abstract **─** In order to study the response of ZnO varistors under the radiation of fast rise-time electromagnetic pulse, an experiment system is built composed of square wave pulse source, coaxial cable, coaxial fixture, attenuator, oscilloscope and insulating gas vessel. Electromagnetic pulse protection characteristics of ZnO varistors are tested and analyzed. Results show that: appearance of negative pulse in the responsive waveform means the completion of field-induced insulator-conductor phase transition for ZnO varistors. Peak value of responsive positive pulse decreases after phase transition, and the residual voltage is generally constant for different pulse strength and widths. The phenomenon of overshoot voltage is observed. Negative pulse is caused by the reflection of electromagnetic wave after the phase transition. The resistance of ZnO after phase transition is less than 50 Ω and decreases linearly along with the increase of incident voltage or field, which leads to a highly nonlinear current-voltage characteristic of ZnO varistors in the radiating electromagnetic environment. Sum of energy of positive and negative pulse keeps constant, which indicates that the weakened positive pulse is converted into negative pulse. So impact of negative pulse needs to be taken into consideration when ZnO varistors are used to protection against strong electromagnetic pulse.

Index Terms **─** Coaxial fixture, fast rise-time electromagnetic pulse, grain boundary theory, insulator-conductor phase transition, nonlinear current-voltage characteristic, quantum tunnelling effect, ZnO varistor.

I. INTRODUCTION

Traditional materials of electromagnetic shielding, such as metal sheet or fiber [1], dope [2], fabric [3, 4], have constant electrical properties and shielding effectiveness. So they don't distinguish useful but weak signals from purposive strong electromagnetic disturbance, which are both shielded. Therefore they are failed to solve the contradiction between strong filed protection and normal operation of equipment. Alternatively, materials such as Zener diodes [5-7], junction field-effect transistors (FET) [8-10], heterogeneous composites filled with conductive particles [11, 12], ZnO-based [13, 14] or VO_2-based [15, 16] metal-oxides and so on, have changeable essential electromagnetic parameters and this change is adaptive and reversible. This type of materials will exhibit highly nonlinear current-voltage resistance switching characteristics or field-induced insulator-conductor phase transition, so they are expected to be used as repeatable transient suppression devices against the effect of strong electromagnetic pulse while some of them are already be used to absorb the voltage surges for circuit protection like metal ZnO arrester (MOA).

For the purpose of protection from fast rise-time electromagnetic pulses like nuclear electromagnetic pulse (NEMP), FET and diodes are unsuited because of their relatively slow response speed. According to IEC61000-2-9 [17], the rise time of NEMP lies in 1.8 ns~2.8 ns, so response time must be less than that values otherwise the peak of NEMP pulse is hard to be rejected. Meanwhile, the materials with the micro-structure of "conducting grains surrounded by thin insulating barriers" like heterogeneous composites filled with conductive particles and some kinds of metal-oxides, can satisfy the requirement of response time and endure the high incident energy, cause that their electrical properties are determined by the theory of grain boundary or quantum tunneling process [18], which is inherently fast as to the

Submitted On: November 12, 2019
Accepted On: February 21, 2020

scale of ~10^{-15} s. So these materials are widely applied in the field of integrated circuit, non-volatile resistive switching memories, sensors and so on [19]. One representative of these materials is ZnO-based metal-oxide varistors which are ceramic semiconductor devices and most used commercially for the protection of power or other low-frequency circuits against lightning or switching surges [20].

However, ZnO varistors are mostly analyzed and applied in the field of circuit protection. Research on the application of ZnO in electric field protection is inadequate, especially for fast rise-time electromagnetic pulse field. In some certain literatures about the response of ZnO against pulses [21-24], ZnO varistors are generally inserted in the circuits as circuit elements, based on the fact that ZnO can absorb the pulse voltage energy to make over-voltage dismiss or decrease rather than to shield pulse using the property of field-induced insulator-conductor phase transition. The former is injecting voltage or current pulses into ZnO varistors, and the latter means electromagnetic pulses are radiated onto ZnO varistors directly.

In this paper we build an experiment system to test the response of ZnO varistors for shielding fast rise-time electromagnetic pulses. A coaxial fixture with ZnO varistor fitted in is designed and manufactured to be an element of the system in order to make ZnO varistor exposed into the radiating fast rise-time electromagnetic pulses environment through coaxial lines. The results are compared with that of [21]. Some differences are found between responsive waveforms by conducting over-voltage pulses in [21] and waveforms by radiating electromagnetic pulses in our work.

II. EXPERIMENTAL PROCEDURES

A. Experiment system

The configuration of coaxial fixture is shown schematically in Fig. 1 and photographically in Fig. 2. The whole fixture is composed of outside conductor (marked by 1 in Fig. 1) and inside conductor (marked by 2 in Fig. 1). The outside and inside conductors both conclude four components connected with each other through thread. The insulating supports (marked by 3 in Fig. 1) are made by Teflon to isolate the conductors and have been grooved annularly to compensate discontinuous capacitance. Due to the reason that the coaxial fixture would be used to propagate very strong electromagnetic pulse and discharge must be refused, the air inlet and outlet (marked by 4 in Fig. 1) are designed to inject and outflow the insulating gas. And also the four zones marked by 5 in Fig. 1 are all chamfered to avoid discharge at sharp points. ZnO varistor with annular shape (diameter not bigger than 43 mm) and certain thickness (1 mm~5 mm) should be placed in the middle of fixture just like that in Fig. 2. According to (1) and (2) [25], the diameters of outside and inside conductors of coaxial fixture are set as 13 mm and 5.65 mm respectively, which makes the characteristic resistance as 50 Ω matched and the theoretical working frequency range from DC to 10.23 GHz:

$$f_c = \frac{2c_0}{\pi(R_1 + R_2)}, \tag{1}$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{R_2}{R_1}\right), \tag{2}$$

where f_c is the cut-off frequency, c_0 is the velocity of light, R_1 and R_2 indicate respectively the diameters of inside and outside conductor, Z_0 means the characteristic resistance of coaxial line and ε_r is the relative dielectric constant of air as 1.

Based on the schematic diagram of Fig. 3, and using the coaxial fixture to clamp the ZnO varistor, the experiment system is built by more other elements like NOISEKEN INS-4040 noise generator, coaxial cables, attenuators, TEK TDS7404B oscilloscope and insulating gas (SF6) vessel as shown in Fig. 4. The NOISEKEN INS-4040 noise generator is used as square wave pulse source and can produce a variety of pulse width such as 50 ns up to 1 μs with the peak value of strength from 10 V up to 4 kV ideally and the rise time from 500 ps to 1 ns, which makes the max value of pulse field strength at the place of fitting materials in the coaxial fixture as almost 1.70 MV/m theoretically calculated by (3) [26]:

$$|\boldsymbol{E}|_{\max} = \frac{2U_0}{R_1 \ln\left(\frac{R_2}{R_1}\right)}, \tag{3}$$

where U_0 is the output peak value of square wave pulse source. Although this value is less than the air breakdown field strength 3 MV/m, we still have found the discharge phenomenon in the coaxial fixture sometimes in the experiment process. So insulating gas such as SF6 is adopted as the standby. The whole system has the matching resistance of 50 Ω for consistent.

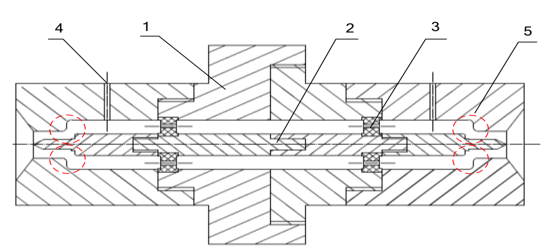


Fig. 1. Schematic diagram of the coaxial fixture.

Fig. 2. Photograph of the coaxial fixture.

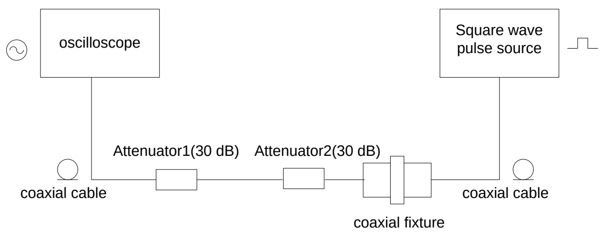


Fig. 3. Schematic diagram of experiment system.

Fig. 4. Photograph of experiment system.

B. Analyses of propagation performance of system

Good propagation performance should be satisfied for avoiding wave distortion, which can be reflected by S11 parameters of system. So S11 curves were obtained through vector network analyzer (VNA) in the frequency range of 300 kHz to 1.5 GHz and 10 MHz to 10.23 GHz respectively, as shown in Fig.5 and Fig. 6. We can see that S11 of this coaxial fixture is less than -10 dB and the standing-wave ratio (SWR) will be less than 2 in the frequency range of 300 kHz to 7.36 GHz, which is enough to ensure the well transmission performance of fast rise-time pulse in this paper. Propagation performance was proved from the output waveforms of system with no material tested shown in Fig. 7, which demonstrates good shape of 1 μs square waveforms. *U* represents the waveforms displayed by oscilloscope. The discrepancy in the frequency range of 7.36 GHz to theoretic 10.23 GHz maybe comes from the machining error, which can be ignored for that most of pulse energy are widely distributed throughout low frequencies.

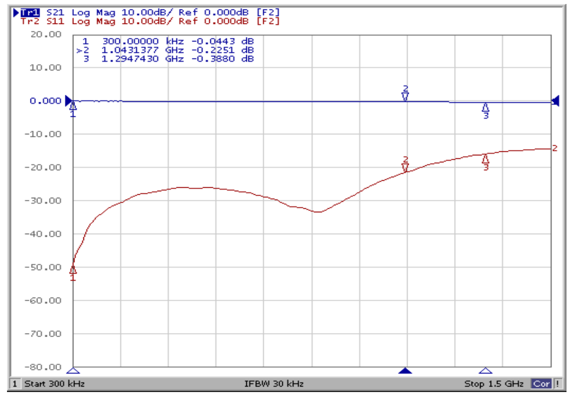


Fig. 5. S11 of coaxial fixture (partially shown in 300 KHz ~1.5 GHz).

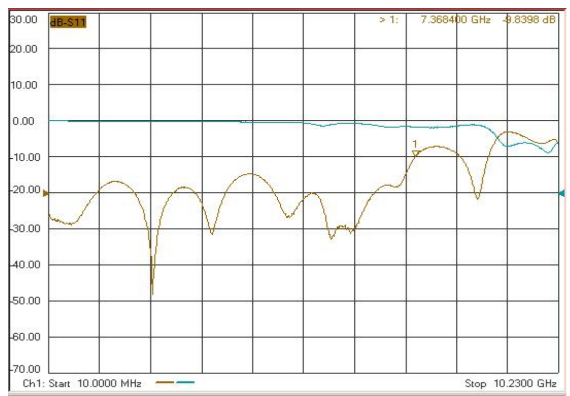


Fig. 6. S11 of coaxial fixture (partially shown in 10 MHz ~10.23 GHz).

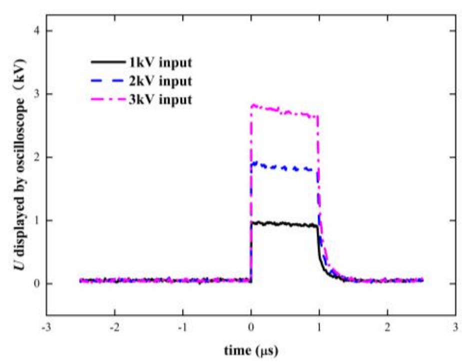


Fig. 7. Output waveforms of system without ZnO varistor fitted in.

C. Analyses of output error of system

Output error of system must be eliminated to assure the accuracy of experiment results. Fig. 8 shows the errors between input and output waveforms. U_i represents the ideal value of input voltage and U_o is the average peak value of output pulses of system in five times triggering. The black solid line with block symbols describes average output peak value of square wave pulse source. The blue dashed line with block symbols describes average error between practical values and ideal values. The black solid line with circular symbols describes the average output peak value of system under the situation that the coaxial fixture is connected with the pulse source and no ZnO varistor is fitted in. The blue dashed line describes average error between practical values and ideal values. It is obviously that errors introduced by the coaxial fixture are very little and can be dismissed. Good propagation performance has been satisfied, so errors introduced by coaxial cables and attenuators can be dismissed. Most of the errors come from the pulse source itself. As the practical output peak value of square wave pulse source is 3.621 kV, the max value of pulse field strength at the place of fitting materials in the coaxial fixture has to be modified from 1.70 MV/m to 1.54 MV/m.

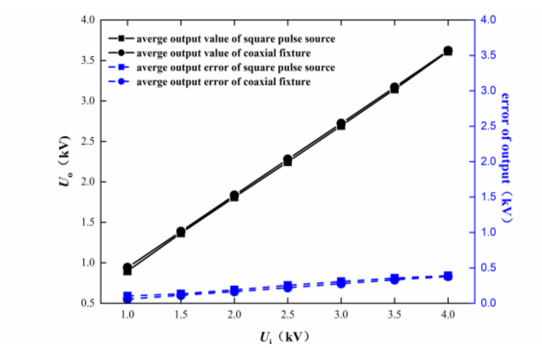
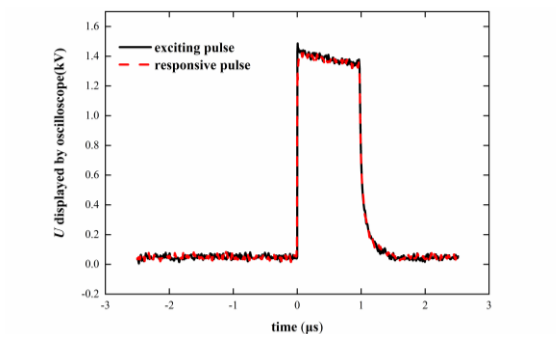


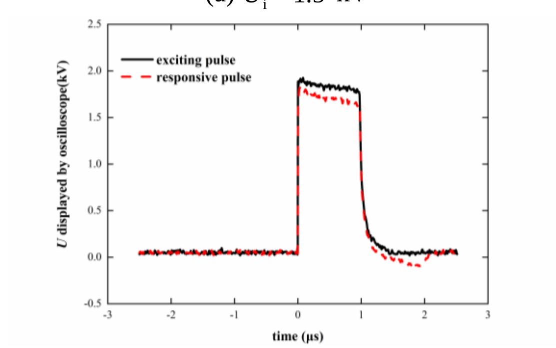
Fig. 8. Average output value and error of square pulse source and coaxial fixture respectively.

D. Analyses of experiment results

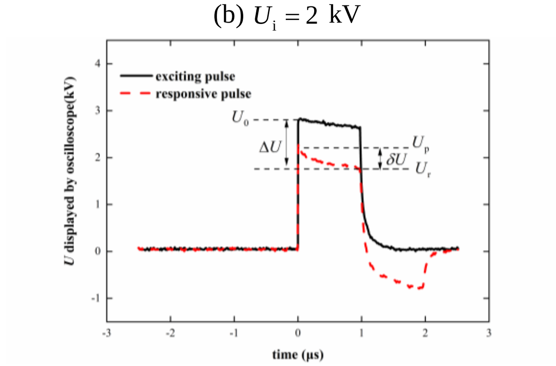
A type of ZnO varistors with the diameter as 34 mm and thickness as 3 mm, which are bought as commercial products with a standard sensitive voltage as 700V in circuits, were fitted in the coaxial fixture and tested by this experiment system. Before testing, the silver plated on both sides of ZnO have been erased, as the silver layer would cause the electromagnetic wave to be completely reflected. The responsive pulse waveforms and exciting pulse waveforms are both shown in Fig. 9 with pulse width as 1 μs and a series of input pulse voltages. As we can see from the figures, the output responsive pulse is same as the input exciting pulse when the input voltage is less than 2 kV mainly. This result means ZnO varistor is still a good insulator and doesn't affect the propagation of electromagnetic pulse before the input voltage comes bigger than 2 kV. When the input voltage increases over 2 kV mainly (the max electric field in the coaxial fixture is correspondingly almost 850 kV/m), the peak value of output responsive pulse becomes lower than input exciting pulse and negative pulse occurs. As the input voltage increases, the negative pulse increases too. This phenomenon suggests that ZnO varistor has change to be a conductor with certain resistance, which will be explained in detail by Section III of this paper. Under the condition that insulating gas has been injected to avoid discharging along the face of material, the responsive pulse can be observed repeatedly and similarly, which means ZnO varistor maintains the stable performance and is not broken down by strong electric field during the process of experiment. So conclusion can be gain as that appearance of negative pulse in the responsive waveforms indicates that field-induced insulator-conductor phase transition has happened simultaneously.



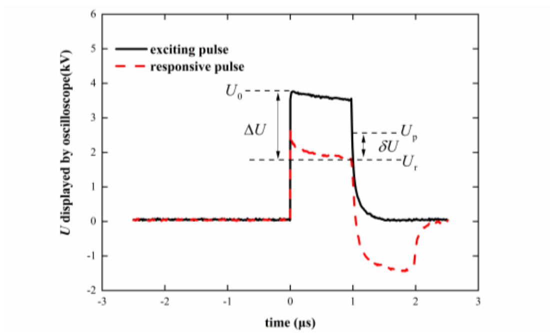
(a) $U_i = 1.5$ kV



(b) $U_i = 2$ kV



(c) $U_i = 3$ kV



(d) $U_i = 4$ kV

Fig. 9. Comparison of exciting pulse waveforms and responsive pulse waveforms in a series of input voltages.

In contrast with the waveforms of input square pulses, there are three changes happened for the responsive waveforms: 1) the peak value of pulse decreases after phase transition; 2) the overshoot voltage exists with the phase transition; 3) the negative pulse emerges and increases as the input increases. Correspondingly, for the purpose of revealing the changing rules, we have observed three aspects of results which are 1) the voltage drops ΔU (shown in Fig. 9) from U_o to U_r, which is the residual voltage after phase transition; 2) the overshoot voltage δU (shown in Fig. 9) from the peak value of responsive pulse U_p to U_r; and 3) the radio distribution of positive pulse energy and negative pulse energy to the whole pulse energy respectively. Relevant values are listed by Table 1, from which we can find that: U_r is a basically constant value as almost 1.7 kV, ΔU and δU increases linearly as input voltage increases. Their respective radio distributions are shown in Fig. 10.

For the first aspect: ΔU, based on Table I and black solid line with block symbols in Fig. 10, we can know that the capability of ZnO to suppress the peak of radiated strong electromagnetic pulse is approximately enhanced linearly as the input voltage increases. The second one: overshoot voltage δU, whose change is shown as red dashed line with circular symbols in Fig. 10, has relationship with the mechanism of phase transition of ZnO and will be discussed in the next section. The last one is demonstrated by Fig. 11, in which energy is calculated with pulse amplitude multiplied by time. We can see that the positive pulse energy decreases and the negative pulse energy increases as the input pulse voltage increases. However, the sum of energy of positive and negative pulses is found to be a constant approximately. This fact means the suppression of input positive pulse is transferred to the increment of negative pulse by ZnO, which need to be taken sincerely into consideration when ZnO is used to protect against fast rise-time electromagnetic pulse.

Table 1: Changes of voltage in the field-induced insulator-conductor phase transition (all in kV)

U_i	U_o	U_p	U_r	ΔU	δU
2	1.835	1.843	1.655	0.21	0.188
2.5	2.28	2.138	1.753	0.527	0.385
3	2.723	2.304	1.761	0.962	0.543
3.5	3.169	2.59	1.763	1.406	0.827
4	3.621	2.635	1.772	1.849	0.863

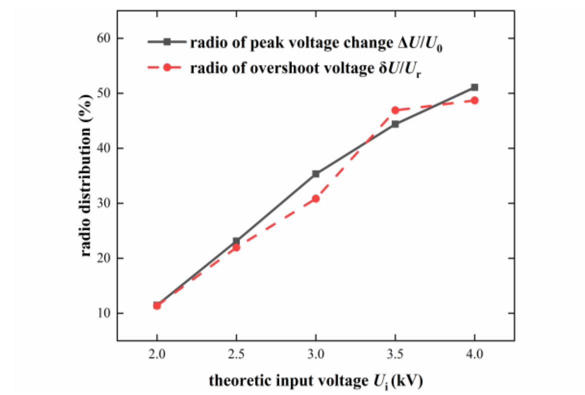


Fig. 10. The radio distribution of ΔU and δU.

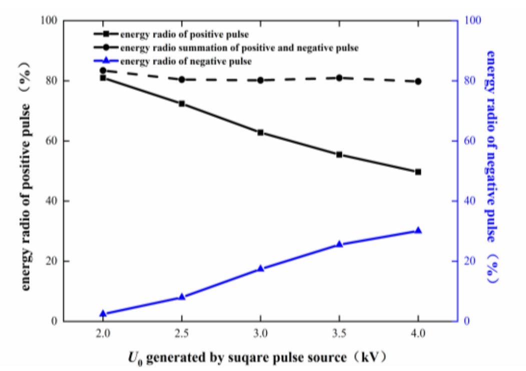


Fig. 11. The radio distribution of positive pulse energy and negative pulse energy to the whole pulse energy respectively.

III. DISCUSSION

For protection of fast rise-time electromagnetic pulse, the electric field threshold of phase transition and the responsive time are two most important indicators that we are concerned about. In the above experiments, the practical voltage threshold of phase transition is almost 1.835 kV (the ideal value is 2 kV), which means the electric field threshold is almost 780 kV/m calculated by (3), for the input pulses with 1 μs width. Father experiments indicate that the threshold of field strength is fixed to this value even though different pulse widths were injected. This is because in the electric field conduction region of ZnO nonlinear resistance (that is, the current-voltage characteristic region with high resistance to low resistance phase transition), the tunneling effect to generate tunnel current is related to the electric field or voltage applied on the grain boundary layer, and have nothing to do with pulse width [18]. Moreover, the quantum tunneling effect is basically in femtosecond, so under the action of electromagnetic pulse with fast rise-time in nanosecond, ZnO can respond in time when the electric field reaches the threshold. This has been proved by the fact that there is no delay between the response waveforms and the input excitation waveforms in all experimental results. The responsive speed is same as that in [21], which is less than or equal to 500 ps. From the above analyses, we can get a conclusion that even though this type of ZnO varistors can meet the requirement of response speed, they may be not suitable for NEMP protection due to their high threshold of electric field strength, which is much bigger than 50 kV/m. According to previous research, the threshold electric field of phase transition has a positive correlation to the thickness of ZnO. Obviously the ZnO varistors we test are too thick to be used as NEMP shielding materials.

Same as the responsive pulses in [21], there exists a constant residual voltage U_{r} with an overshoot voltage δU in our work. Figure 12 shows that the residual voltage U_{r} is generally constant even for different pulse widths. U_{r} represents the shielding capability of ZnO. In the process of experiments, the fact that U_{r} doesn't change with the increase of input electric field has proved that the shielding effectiveness of ZnO is enhanced and adaptable along with the change of incident field. Note that no unified standard about the shielding effectiveness for electromagnetic pulse in time domain has been defined [27, 28], so this paper would not give the exact value of it for ZnO varistors. In addition, the phenomenon of overshoot voltage in ZnO test can also be observed in the circuit experiments. There is no unified view on the cause of its formation in the academic world. An opinion generally accepted is that: when the applied voltage rises, the transition from capacitive current to resistive current passing through ZnO plate needs a certain time delay, which leads to an overshoot in the pulse waveform [18].

However, different from the responsive pulses obtained by injecting fast square wave voltage into ZnO in [21], in which only the peak of pulses decreases and the waveform does not change, for the response pulses of ZnO irradiated by fast square electromagnetic pulse, not only the peak deceases, but also the negative pulse emerges. In order to verify the reason of the negative pulse, a 20 m coaxial transmission line was adopted to substitute the original one (almost 0.2 m) to propagate the pulse. From the result shown by Fig. 13, we can see that the part of negative pulse has a time delay from the part of positive pulse, and the time delay is just the propagation time of electromagnetic pulse forward and backward along with the 20 m transmission line (time delay $\Delta t = 2\times 20\ \mathrm{m}/v$; v is the velocity of electromagnetic wave in the coaxial line and $v = c/\sqrt{\varepsilon_r}$ [29]; c is the velocity of light in the vacuum; ε_r is the permittivity of insulating medium in the coaxial line and $\varepsilon_r \approx 2.5$). So, the negative pulse indicates that ZnO varistors has occurred high-to-low resistance switching phase transition. It is considered to be a reflected signal generated by the mismatch between the low resistance of ZnO and the system impedance 50 Ω. According to the transmission line theory [26], the low resistance of ZnO after phase transition can be calculated by below equations:

$$\Gamma = \frac{Z_{\mathrm{L}} - Z_0}{Z_{\mathrm{L}} + Z_0} = \frac{U_{\mathrm{p}}^{'}}{U_{\mathrm{p}}}, \tag{4}$$

$$Z_{\mathrm{L}} = Z_0 \frac{1+\Gamma}{1-\Gamma}, \tag{5}$$

where U_{p} is the peak value of positive pulse and $U_{\mathrm{p}}^{'}$ is the peak value of negative pulse; Γ is the reflection coefficient in the end of transmission line; Z_0 is the equivalent impedance of coaxial line and $Z_0 = 50\ \Omega$; Z_{L} is the equivalent impedance of ZnO varistors. Note that for the purpose of simplifying calculation, here the dispersive capacitances of transmission line and ZnO varistors are dismissed and all the impedance is seemed as pure resistance. The calculated results are listed in Table 2, from which we can see that: the resistance of ZnO after phase transition is less than 50 Ω and decreases linearly along with the increase of incident voltage or field. Though the current of coaxial transmission line cannot be generally measured directly and is also not easily calculated by the equation in [21] due to the emergence of negative pulse, it is still clear to conclude that the current-voltage characteristic of ZnO varistors in the radiating electromagnetic environment is nonlinear based on the relationship of current, voltage and resistance, which agrees with the conductive mechanism of ZnO based on double Schottky barrier model [18].

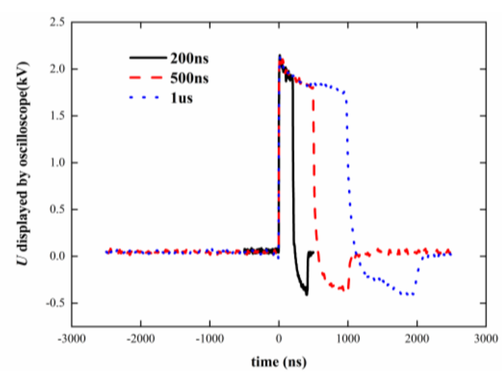


Fig. 12. The responsive waveforms of ZnO varistor with the 2.5 kV voltage but different pulse widths inputted.

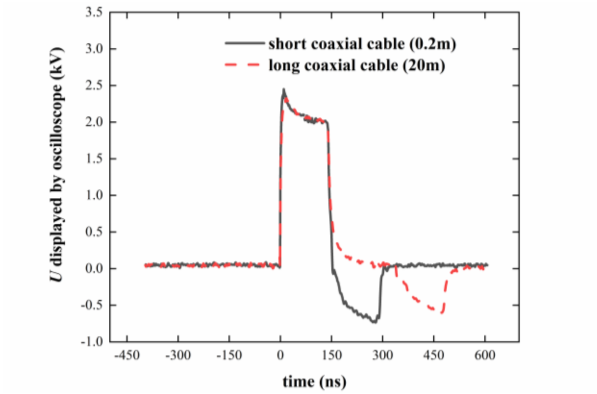


Fig. 13. The responsive waveforms of ZnO varistor with the 3 kV voltage and 150 ns pulse width inputted using the coaxial cable with different lengths.

Table 2: Impedance calculation of ZnO varistors (voltage in kV, impedance in Ω)

U_i	U_p	U_p'	Γ	Z_L
2	1.843	-0.09	-0.049	45
2.5	2.138	-0.41	-0.192	34
3	2.304	-0.792	-0.344	24
3.5	2.59	-1.155	-0.446	19
4	2.635	-1.425	-0.541	15

IV. CONCLUSION

In this paper, an experimental system to test the response of ZnO for shielding fast rise-time electromagnetic pulses is built by using a coaxial fixture with gas insulation design. The electromagnetic pulse protection characteristics of ZnO varistors are measured and analyzed. The results show that:

1) The coaxial fixture has good transmission performance, and the actual S11 parameter is less than -10 dB in the range of 300 kHz to 7.36 GHz, introducing a very small test error to the experiment system. Analyses of output error shows that most of the errors come from the pulse source itself.

2) The insulator-conductor phase transition occurs when the 1.835 kV pulse is irradiated onto the surface of ZnO varistor, which means the threshold of electric field strength is 780 KV/m approximately. A negative pulse waveform appears after phase transition, which is different from that in the past studies when ZnO is injected with an overvoltage pulse.

3) There is no delay between the responsive waveforms and the input excitation waveforms, which indicates that the responsive speed of ZnO is less than or equal to 500 ps, so ZnO can respond in time when the electric field reaches the threshold.

4) The peak value of positive pulse decreases after phase transition, and the residual voltage is generally constant for different pulse strength and widths, which has proved that the shielding effectiveness of ZnO is enhanced and adaptable along with the increase of incident field. The phenomenon of overshoot voltage is observed, and overshoot voltage increases linearly as the input radiating pulse field strength increases.

5) The appearance of negative pulse in the waveform means the completion of field-induced insulator-conductor phase transition. Negative pulse is caused by the reflection of electromagnetic wave after the phase transition. The resistance of ZnO after phase transition is less than 50 Ω and decreases linearly along with the increase of incident voltage or field, which leads to the highly nonlinear current-voltage characteristic of ZnO varistors in the radiating electromagnetic environment.

6) Sum of energy of positive and negative pulses keeps constant, which means that the weakened positive pulses are converted into negative pulses. So impact of the negative pulse needs to be taken into consideration when ZnO varistors are used to protection against strong electromagnetic pulse.

In conclusion, there are some similarities and some differences between the results obtained by injecting fast square wave voltage into ZnO in previous works and that obtained by radiating square wave pulse onto ZnO surface in our work. This may possess certain reference value for solving the problem of electromagnetic pulse defense. What need to be added is that: due to the similarity in frequency distribution and fast rise time between square wave and NEMP, we use square waveform pulse source to substitute NEMP generator. Continuous wave usually lacks enough strength to induce phase transition of ZnO. The response for pulse with other waveforms can be observed by using corresponding pulse source to replace the pulse source in the existing system.

We wish to emphasize that the results presented here are preliminary. The varistors materials we used were not optimized for specific application of NEMP protection. The relationship between the thickness of ZnO varistors and the threshold field strength requires clarification. Meanwhile, the impact of negative pulse on protective effectiveness for electromagnetic pulse also needs further studies. These questions may be answered in following papers.

ACKNOWLEDGMENT

Thanks to Mr. Zhang Nanfa for his theoretical guidance.

Research of this paper has been funded by pre-research project of the 13th five-year plan in China.

REFERENCES

[1] W. Jianzhong, M. Jun, Z. Hao, and T. Huiping, "Preparation and electromagnetic shielding effectiveness of metal fibers/polymer composite,"

Rare Metal Materials & Engineering, vol. 46, pp. 73-77, 2017.

[2] Z. Shuang-Xi, H. Shui-Mei, D. Wen-Wu, X. Qing, and W. Wei-Dong, "Research progress of doped electromagnetic shielding conductive coatings," *Bulletin of the Chinese Ceramic Society*, vol. 31, pp. 604-608, 2012.

[3] J. P. Blanchard, F. M. Tesche, S. H. Sands, and R. H. Vandre, "Electromagnetic shielding by metallized fabric enclosure: theory and experiment," *Electromagnetic Compatibility IEEE Transactions on*, vol. 30, pp. 282-288, 1988.

[4] X. Zhu and X. Li, "Current status and research direction of electromagnetic shielding fabric," *Shanghai Textile Science & Technology*, vol. 1, pp. 104-107, 2010.

[5] T. Matsushima, M. Aoki, T. Hisakado, and O. Wada, "Equivalent circuit model with nonlinear characteristics of zener diode extracted from SPICE model for ESD simulation," in *Electromagnetic Compatibility of Integrated Circuits*, pp. 152-155, 2017.

[6] O. C. Spro, S. Basu, I. Abuishmais, O. M. Midtgard, and T. Undeland, "Driving of a GaN enhancement mode HEMT transistor with zener diode protection for high efficiency and low EMI," in *European Conference on Power Electronics and Applications*, pp. P.1-P.10, 2017.

[7] Y. Cheng, H. Xianjun, and L. Peiguo, "Protection and simulation of energy selective surface based on voltage conductive structure," *Chinese Journal of Ship Research*, vol. 7, pp. 98-103, 2012.

[8] X. Tang, H. Gao, S. Pan, J. Sun, X. Yao, and X. Zhang, "Electrical characteristics of individual In-dop ed ZnO nanob elt field effect transistor," *Acta Physica Sinica*, vol. 63, pp. 314-319, 2014.

[9] L. Yuan, H. Chen, Q. Zhou, C. Zhou, and K. J. Chen, "Gate-induced Schottky barrier lowering effect in AlGaN/GaN metal–2DEG tunnel junction field effect transistor," *IEEE Electron Device Letters*, vol. 32, pp. 1221-1223, 2011.

[10] W. Zhang, M. Li, Q. Wei, L. Cao, Z. Yang, and S. Qiao, "Fabrication and I-V characteristics of ZnO nanowire-based field effect transistors," *Acta Physica Sinica*, vol. 57, pp. 5887-5892, 2008.

[11] X. Wang, J. Guo, Y. Yao, Z. Jia, Q. Lv, and R. Huang, "Study of epoxy resin composites doped with nonlinear fillers and its electrical properties," in *IEEE Conference on Electrical Insulation and Dielectric Phenomenon*, pp. 54-57, 2017.

[12] X. Wang, S. Herth, T. Hugener, and R. W. Siegel, "Nonlinear Electrical Behavior of Treated ZnO-EPDM Nanocomposites," in *Electrical Insulation and Dielectric Phenomena, 2006 IEEE Conference on*, pp. 421-424, 2006.

[13] M. Y. Song, Y. Seo, S. Park, J. H. Lee, H. M. An, and T. G. Kim, "Observation of highly reproducible resistive-switching behavior from solution-based ZnO nanorods," *Journal of Nanoscience & Nanotechnology*, vol. 13, p. 6212, 2013.

[14] E. J. Yoo, J. H. Kim, J. H. Song, T. S. Yoon, Y. J. Choi, and C. J. Kang, "Resistive switching characteristics of the Cr/ZnO/Cr structure," *Journal of Nanoscience & Nanotechnology*, vol. 13, p. 6395, 2013.

[15] R. Hao, Y. Li, F. Liu, Y. Sun, J. Tang, P. Chen, *et al.*, "Electric field induced metal–insulator transition in VO 2 thin film based on FTO/VO 2/ FTO structure," *Infrared Physics & Technology*, vol. 75, pp. 82-86, 2016.

[16] J. Jeong, N. Aetukuri, T. Graf, T. D. Schladt, M. G. Samant, and S. S. Parkin, "Suppression of metal-insulator transition in VO2 by electric field-induced oxygen vacancy formation," *Science*, vol. 339, pp. 1402-5, 2013.

[17] Y. Z. Xie, Z. J. Wang, Q. S. Wang, and H. Zhou, "Comparison of several HEMP waveform standards," in *Radio Science Conference, 2004. Proceedings. 2004 Asia-Pacific*, pp. 516-518, 2005.

[18] W. WU, J. He, and Y. Gao, *Properties and Applications of Nonlinear Metal Oxide Varistors*. Beijing: Tsinghua University Press, 1998.

[19] Z. Yang, C. Ko, and S. Ramanathan, "Oxide electronics utilizing ultrafast metal-insulator transitions," *Annual Review of Materials Research*, vol. 41, pp. 337-367, 2011.

[20] J. He, J. Lin, J. HU, and W. Long, "Development of ZnO varistors in metal oxide arrestors utilized in ultra high voltage systems," *High Voltage Engineering*, vol. 37, pp. 634-643, 2011.

[21] H. R. Philipp and L. M. Levinson, "ZnO varistors for protection against nuclear electromagnetic pulses," *Journal of Applied Physics*, vol. 52, pp. 1083-1090, 1981.

[22] F. A. Modine and R. B. Wheeler, "Fast pulse response of zinc-oxide varistors," *Journal of Applied Physics*, vol. 61, pp. 3093-3098, 1987.

[23] F. A. Modine, R. B. Wheeler, Y. Shim, and J. F. Cordaro, "Origin of the pulse response characteristics of zinc oxide varistors," *Journal of Applied Physics*, vol. 66, pp. 5608-5612, 1989.

[24] F. A. Modine and R. B. Wheeler, "Pulse response characteristics of ZnO varistors," *Journal of Applied Physics*, vol. 67, pp. 6560-6566, 1990.

[25] X. Chen, "Testing and modeling for shielding effectiveness of planar materials against electromagnetic pulse" *Doctorate, Ordnance Engineering College*, Shijiazhuang, China, 2013.

[26] X. Zhou, *Microwave Technology and Antenna*. Nanjing: Southeast University Press, 2009.

[27] B. Zhou, G. Cheng, and H. Ren, "The definition

of EMP shielding effectiveness," in *Asia-Pacific Conference on Environmental Electromagnetics Ceem*, pp. 562-565, 2003.
[28] L. Klinkenbusch, "On the shielding effectiveness of enclosures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 47, pp. 589-601, 2005.
[29] J. Gu, *Microwave Technology*. Beijing: Science Press, 2009.

Yun Wang was born in China, 1985. He received Ph.D.'s degree in Information and Communication Engineering from the Academy of Equipment in Beijing, China, 2010. He is currently a Researcher in Department of Science and Technology of Henan Province, Zhengzhou, China. His research interests are electromagnetic pulse shielding and antennas.

Wangwei Zhang was born in China, 1983. He received doctor's degree in Theory and Technology of Weapon Launching from Ordnance Engineering College in Shijiazhuang. He is currently a University Teacher in Zhengzhou University of Light Industry in Zhengzhou. His research interests are Equipment Modeling and Simulation.