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Study of Nonlinear Effect on Electronic System Induced by TVS Limiter When Illuminated by HPEM Pulse

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Abstract—This paper studies the nonlinear effects induced by a TVS limiter on an entire system illuminated by a high power electromagnetic (HPEM) pulse through a simple model. The relations between the load responses and the incident electric field under different conditions are obtained numerically. The results show that the TVS limiter not only protects the circuit which it is intended to but also may increase the response of the other end which is connected to the circuit by a transmission line. The nonlinear effect of the TVS limiter on the other end is dependent on the incident direction of the external HPEM pulse, TVS location, line length, electric field level, and shielding cavity. When the effective coupling length (ECL) of a load is longer than the line length, or its coupling with external HPEM is much weaker than the other end, its response will be affected by the other end connected with a TVS limiter and will become nonlinear. The addition of a shielding cavity will increase the effect because the cavity will increase the duration of the field which results in a larger ECL. Due to the nonlinear effect of the TVS limiter, special attentions, such as considering different incident directions as many as possible in the real testing and setting more margins, should be paid in the protection design.

1. INTRODUCTION

High power electromagnetic (HPEM) pulses, such as high-altitude electromagnetic pulse (HEMP) and lightning electromagnetic pulse (LEMP), can cause upset or damage on electronic systems.

Protection devices, such as transient voltage suppressors (TVS) and filters, are always employed to protect susceptible devices inside the systems against electromagnetic interference [1–3]. Due to high power, HPEM pulses can cause nonlinear effects on electronic systems. Nonlinear effects usually happen in two cases. One is that large Electromagnetic Inference (EMI) turns a protection device into the work state, which will result in the nonlinear response of systems; the other is that circuits and devices within systems have nonlinear effects, such as upset and damage.

To design system protection, low-level field testing, CW or pulse field illumination is always applied first to get the low-level response of systems [4]. Then the EMI generated by the HPEM pulse is obtained by linear extrapolation. Based on the extrapolated EMI, a protection measure is determined. However, this linear extrapolation may be inaccurate, and there may be nonlinear effects existing in systems. Even though high-level testing is applied, due to the very limit of the incident direction and polarization direction of the field generated by simulators, the results cannot represent all the cases. As a result, the nonlinear responses of electronic systems, when being illuminated by HPEM pulses, are important to study for the protection design.

Nonlinear effects of EMI on circuits have been studied by some researchers [5, 6], and much study has been focused on the damage effect or damage mechanism of devices induced by external HPEM

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pulse [7–11]. Also, some computational methods, such as the finite-difference time-domain, hybrid S-parameters, and SPICE model, have been proposed to analyze EMP coupling with systems including nonlinear devices [12–15]. However, few researches focus on the nonlinear effects induced by protection devices, such as TVS limiters, when the system is illuminated by external HPEM pulses.

Protection devices are an important factor which will result in nonlinear responses of systems. As a protection device is introduced to protect a circuit inside a system, its influences on other circuits are unknown when the system is illuminated by external HPEM pulses. This paper studies the nonlinear effects induced by a TVS limiter on an entire system illuminated by an HPEM pulse through a simple model, especially the effect on the other end which is connected to the TVS limiter via a transmission line. In the study, the transmission line is assumed lossless. The results show that the TVS limiter not only protects the circuit with which it is connected but also may increase the response of the other end which is connected to the circuit by a transmission line. The effects of the TVS limiter on the other end under different conditions are studied. Based on the study, some suggestions for the protection design are given.

2. MODEL AND METHOD

Figure 1 shows a simple model, where two circuits are represented by loads R_1 and R_2 at end A and end B of a transmission line, respectively, which is illuminated by an HPEM pulse. The line is 5 cm high over an infinite and perfectly conducting ground, and its radius is 1 mm. The two terminals are matched, that is, both loads are 276 Ω. One load is protected by a TVS limiter of type 1.5KE39CA. The HPEM pulse is chosen to be HEMP, and it can be described by a biexponential pulse as $E_0(t) = kE_0[\exp(-\beta t) - \exp(-\alpha t)]$, where $k = 1.3$, $E_0 = 50\,\mathrm{kV/m}$, $\alpha = 6.0 \times 10^8\,\mathrm{s}^{-1}$, and $\beta = 4.0 \times 10^7\,\mathrm{s}^{-1}$. The definitions of the incident and polarization directions of HEMP are given in Figure 2.

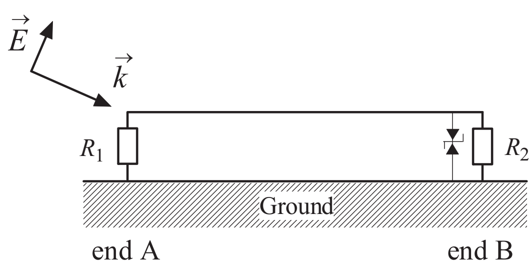

Figure 1. A simple model with a TVS limiter.

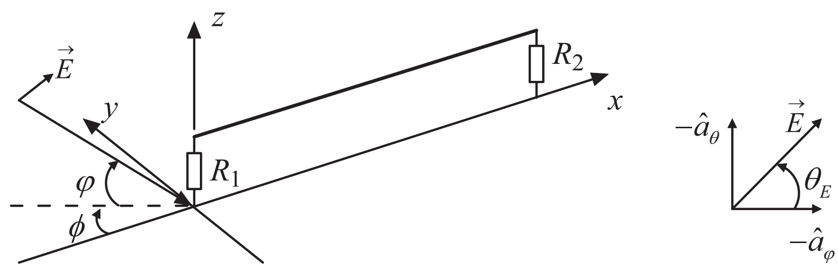

Figure 2. The definitions of the incident and polarized angles.

The trends of currents of the loads versus the electric field under different conditions, where different HEMP incident directions, line lengths, TVS locations, etc. are considered, are computed to study the nonlinear effects induced by the TVS limiter on both ends. The case of the model with a shielding cavity is also investigated to study the nonlinear effect induced by the TVS when a shielding cavity exists. In the simulation, the SPICE model of transmission line illuminated by a plane wave is employed for the case without a shielding cavity [16], while in the case with a shielding cavity, the finite-difference

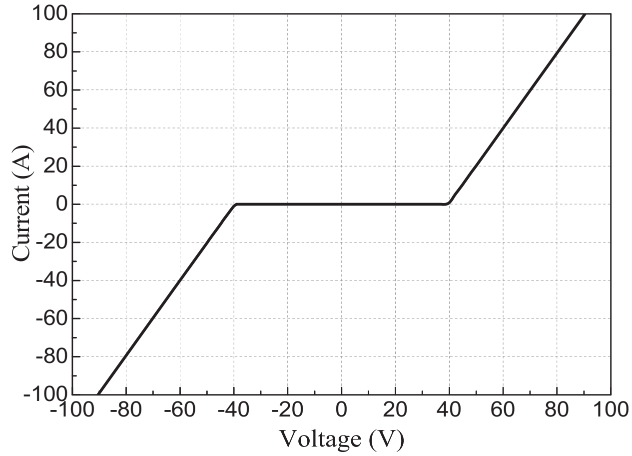

Figure 3. The v-i curve of the 1.5KE39CA TVS limiter.

time-domain (FDTD) method is employed to compute the incident fields of the transmission line first, and then the SPICE model of transmission line excited by nonuniform fields is applied to compute the responses [17]. The behavior of the TVS limiter is represented by its v-i property, as shown in Figure 3 and is realized by a controlled source in the SPICE simulation. Although the v-i property of the TVS limiter cannot represent its exact behavior in the transient case, it does not affect the trend of the nonlinear effect here. All the simulations are carried out in PSpice software.

3. RESULTS AND ANALYSIS

3.1. Effects Induced by TVS for Different TVS Positions

In this section, the current responses at two ends are computed when the TVS limiter is connected at different ends. The transmission line is 2 m long. The elevation angle θ, azimuthal angle φ, and polarized angle θ_E defined in Figure 2 are 30°, 15°, and −90°, respectively.

3.1.1. When the TVS Limiter Is Connected to the Load R_1 in Parallel at End A

The current magnitudes of loads R_1 and R_2 versus the electric field magnitude are computed and shown in Figure 4 Because the TVS limiter of 1.5KE39CA begins to breakdown at 39 V, it turns into the work state, and the voltage of R_1 begins to be clamped when current of R_1 reaches 0.14 A, as shown in Figure 4(a). Hereafter, the relation between the current of R_1 and the electric field is nonlinear.

Figure 4(b) shows the current magnitude of R_2 changing with the electric field magnitude. The black solid line represents the simulation result, while the red dashed line denotes the linearly extrapolated result obtained from the numerical data of 0.5 kV/m, where the TVS limiter is at the off state. It can be seen that the numerical result differs from the linearly extrapolated result since the electric field is 1 kV/m. This implies that the relation between the current of R_2 and the electric field is no longer linear even though there is not a TVS limiter at end B. This means that in this case the TVS limiter has nonlinear effect on the response of the other end.

Figure 5 shows currents of all the loads and the equivalent resistance of end A when the electric fields are 0.5, 1, and 2 kV/m, respectively. When the electric field is 0.5 kV/m, the TVS limiter is at the off state, and the ends of the line are matched. However, when the electric field is 1 kV/m, the TVS limiter turns into the work state, and the equivalent resistance of end A is 180 Ω at minimum, which is not matched any more. Then the unmatched end A reflects the coupled signal, and the reflected signal propagates along the line and then adds to the coupled signal at end B. However, the reflected current is not large enough, as shown in Figure 5(b), thus the current magnitude of R_2 does not change, and its relation with the electric field remains linear. When the electric field is as large as 2 kV/m, the equivalent resistance of end A is 60 Ω at minimum, as shown in Figure 5(c). Then a large reflected

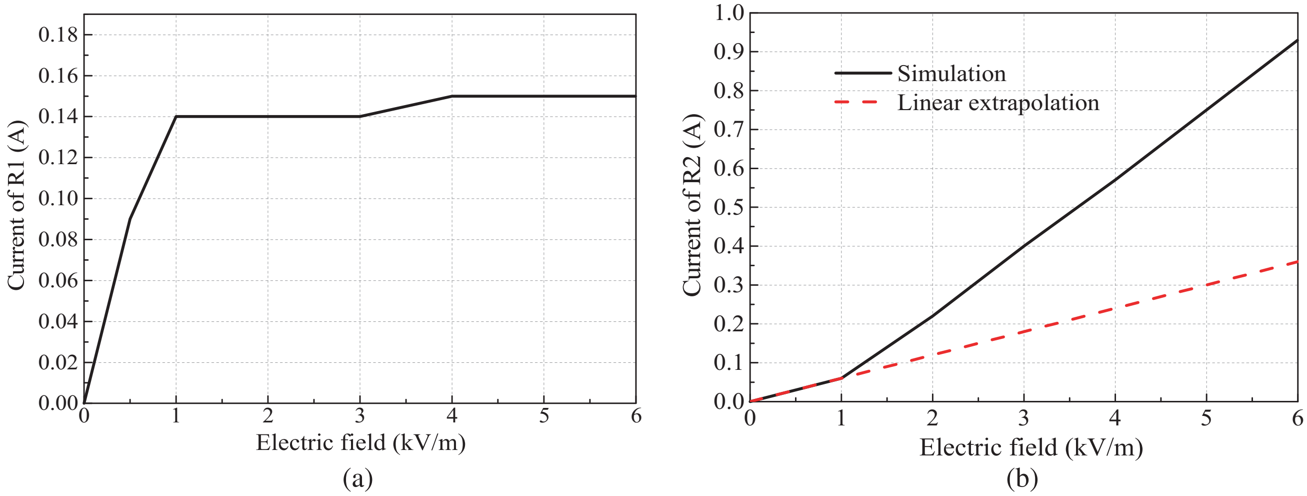

Figure 4. The magnitudes of coupled currents versus the magnitude of incident electric field when the TVS at the end A and the line is 2 m long. (a) Current of R_1. (b) Current of R_2.

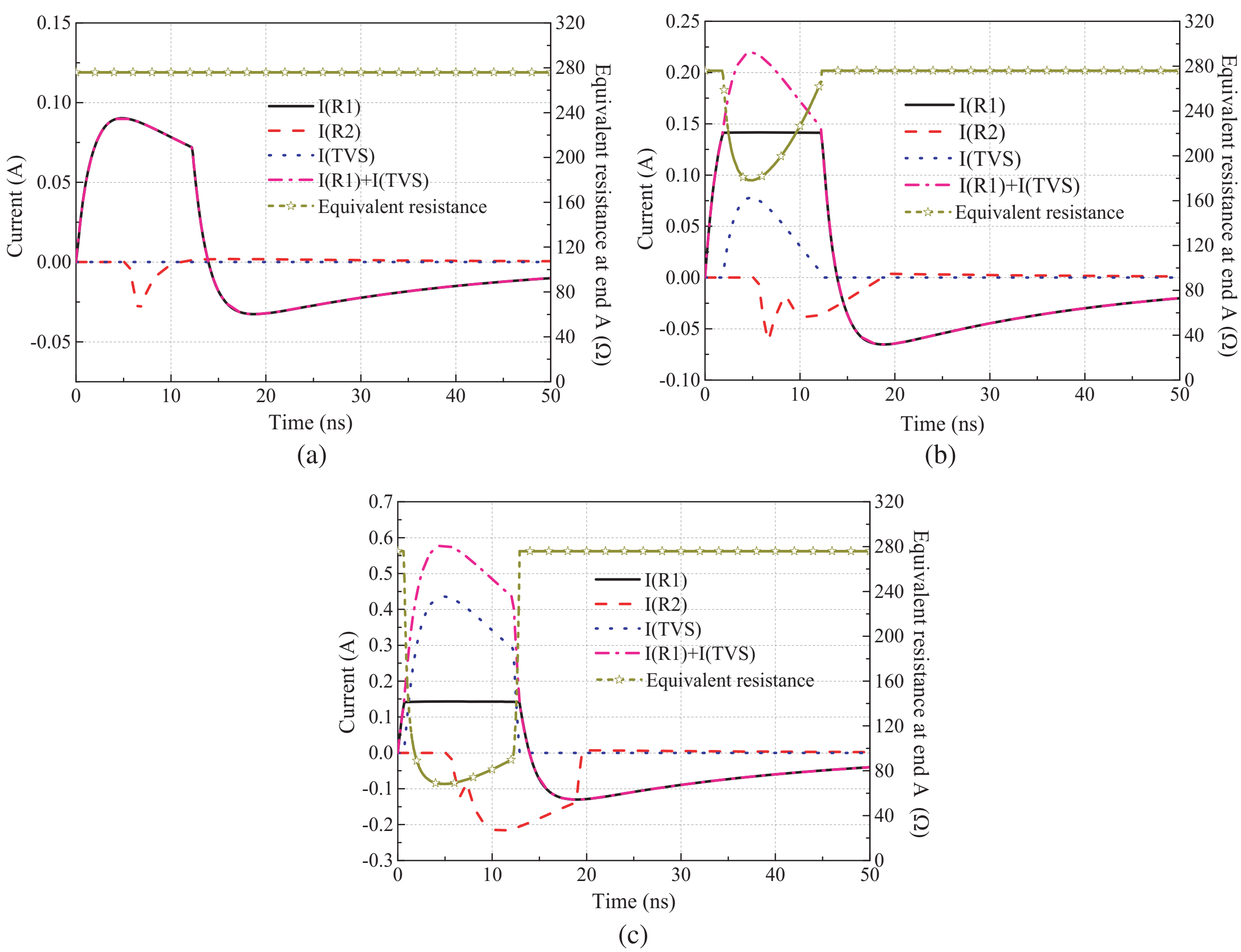

Figure 5. Current of the loads and equivalent resistance of end A for different electric fields when TVS is connected at end A. (a) 0.5 kV/m. (b) 1 kV/m. (c) 2 kV/m.

current will add to the direct coupled current of R_2 and results in the increase of the magnitude, which makes the nonlinear relation between the current of R_2 and the electric field.

3.1.2. When the TVS Limiter Is Connected to the Load R_2 in Parallel at End B

The current magnitudes of loads R_1 and R_2 versus the electric field magnitude are computed and shown in Figure 6. Compared with the above case, the relation between the current and electric field of R_2 is very similar to that of R_1 above, while the relation of R_1, which is at the end without the TVS, is different from that of R_2 above. In this case, the current of R_1 changes linearly with the electric field, as shown in Figure 6(a). This means that in this case the TVS limiter does not have nonlinear effect on the response of the other end.

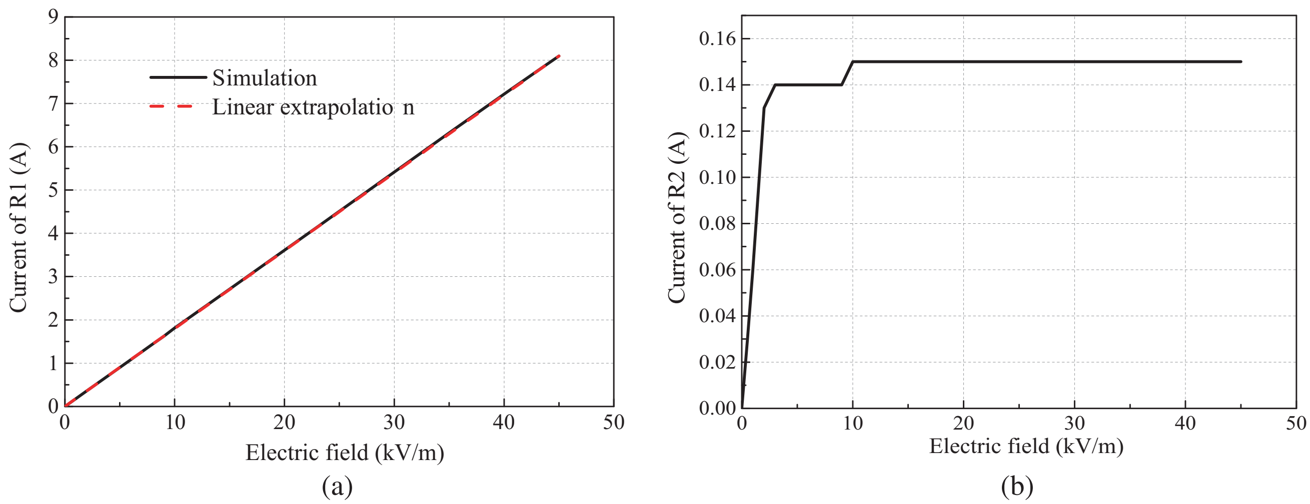

Figure 6. The magnitudes of coupled currents versus the magnitude of incident electric field when the TVS at end B and the line is 2 m long. (a) Current of R_1. (b) Current of R_2.

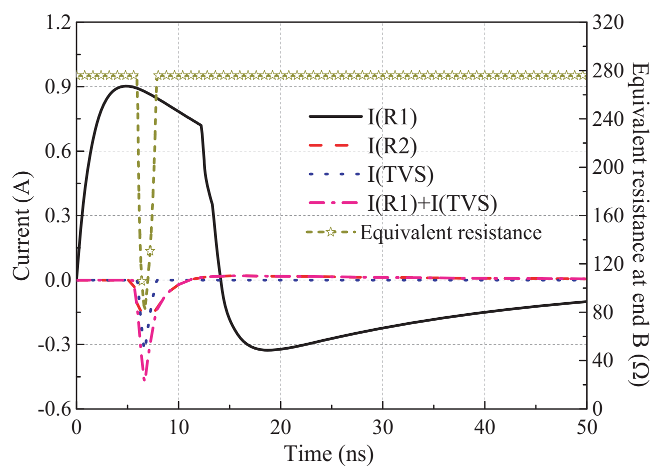

Figure 7. Current of the loads and equivalent resistance of the end B when TVS is connected at end B and the electric field is 5 kV/m.

Figure 7 shows currents of the loads and the equivalent resistance of end B when the electric field is 5 kV/m. The equivalent resistance of end B can reach 83 Ω at minimum, but the reflected current has no influence on the current of end A. This is because the effective coupling length (ECL) of end A is short for the incident direction of HEMP in this case.

ECL is a critical length of the transmission line when the coupled signal, which is generated by external EMP, does not increase with the line length any more [18, 19]. The value of the ECL depends on the line parameter, such as line height, and EMP parameters, such as the incident direction and width. Figure 8 shows the currents of R_1 and R_2 changing with the line length when the ends are matched. The ECLs of R_1 and R_2 are less than 2 m and about 8 m, respectively, in this case. When the ends are not matched, the ECLs may become larger due to the reflection induced by unmatched ends. Because ECL of the end A, which is the near end in this case, is less than 2 m, which is the length of the line, the reflection induced by end B does not affect the current magnitude of end A. However, the ECL of end B, which is the far end, is much larger than 2 m, so the reflected signal of end A (the near end) affects the current magnitude of end B (the far end), which results in the nonlinear relation between the current and the electric field of end B.

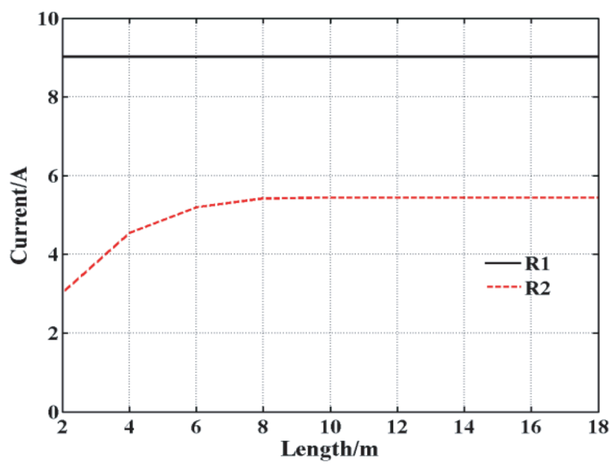

Figure 8. ECL for the loads R_1 and R_2 when the elevation angle θ, the azimuthal angle φ, and the polarized angle θ_E are 30°, 15°, and −90°, respectively.

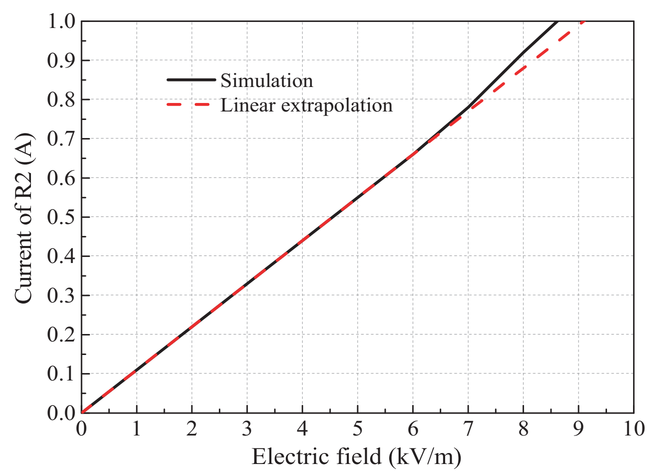

Figure 9. The current of R_2 versus incident electric field when the TVS at end A and the line is 30 m long.

Generally, the ECL of the near end is shorter than that of the far end. Thus the response of the far end is more easily affected by the TVS on the other end than that of the near end.

3.2. Effects Induced by TVS for Different Line Lengths

When the TVS is connected at end A, and the line is 2 m long, there is a nonlinear relation between the current and the electric field at end B, as shown in Figure 4. To study the effects induced by the TVS for different line lengths, the line length is set to 30 m, and the results are shown in Figure 9. When the electric field is below 6 kV/m, the current of R_2 changes linearly with the electric field, which is different from the results when the line is 2 m long. It can be concluded from the results that increase of the line length can reduce the nonlinear effect induced by the TVS on the other end of the line.

However, when the electric field is larger than 6 kV/m, the relation between the current and electric field becomes nonlinear even though the line is longer than the ECL of the matched case. This is because the coupling of HEMP to R_2 is weaker than that to R_1, as shown in Figure 8. The behavior of the TVS limiter can be thought as a nonlinear resistance. The larger the voltage is at the terminals, the smaller the nonlinear resistance is. When the electric field is small, as shown in Figure 10(a), the equivalent resistance of end A is about 68 Ω, and the reflection induced by the nonlinear end A is not large enough to affect the current magnitude of another end. However, when the electric field is large enough, as shown in Figure 10(b), the equivalent resistance is about 17 Ω, and the reflected signal is larger than the direct coupling to end B, which results in the nonlinear relation of the other end (end B).

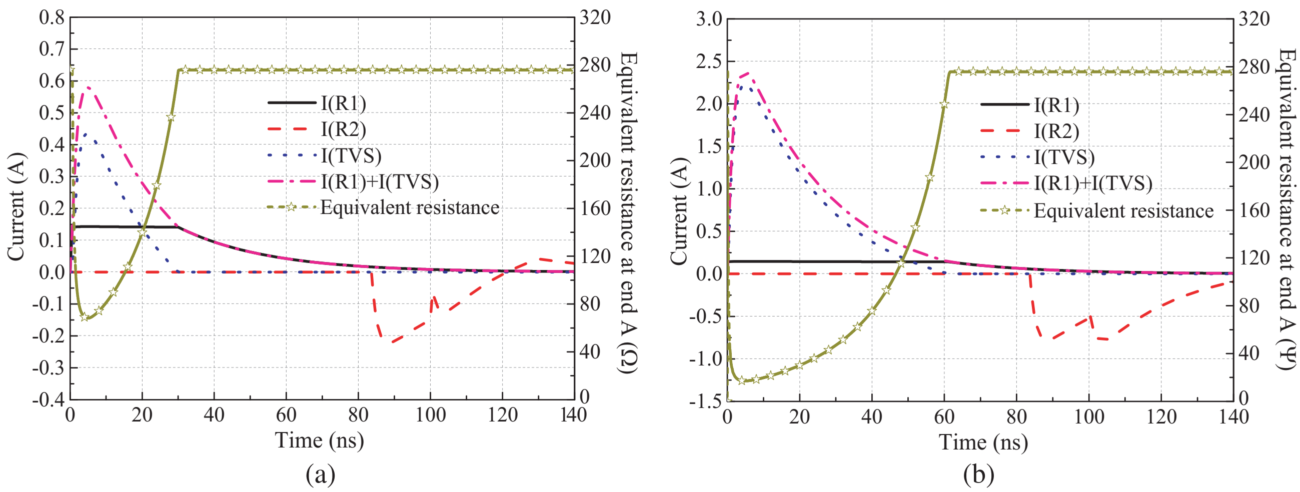

Figure 10. Current of the loads and equivalent resistance of end A for different electric fields when the line is 30 m long. (a) 2 kV/m. (b) 7 kV/m.

3.3. Effects Induced by TVS for Different Incident Directions

To study the effects induced by the TVS for different incident directions of HEMP, the elevation angle θ, azimuthal angle φ, and polarized angle θ_E are set to 90°, 0°, and −90°, respectively, where the line is illuminated by HEMP from above directly. Other parameters are the same as those in Section 3.1. The TVS limiter is connected at end A. Figure 11 shows that the current of R_2 versus the electric field and the relation between them are linear, which is different from that in Section 3.1 shown in Figure 4. This is because for the configuration without the TVS under HEMP of this incident direction, both ECLs of R_1 and R_2 are less than 2 m, and the couplings of the two ends have almost the same size, as shown Figure 12. Thus the reflection of the nonlinear end (end A here) does not affect the current magnitude of the other end (end B here).

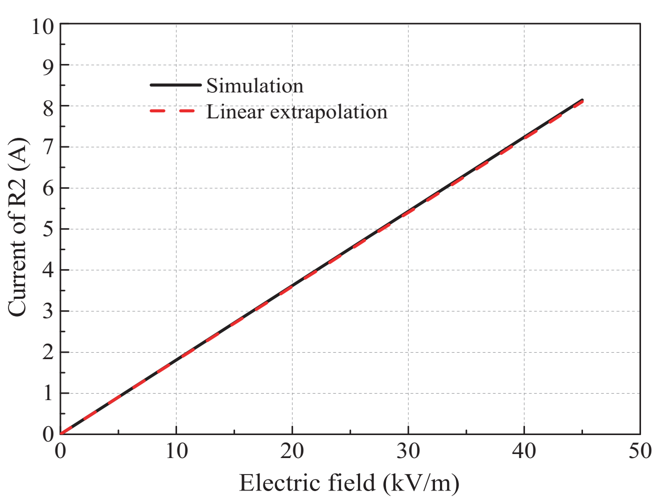

Figure 11. The current of R_2 versus incident electric field when the line is illuminated by HEMP from above.

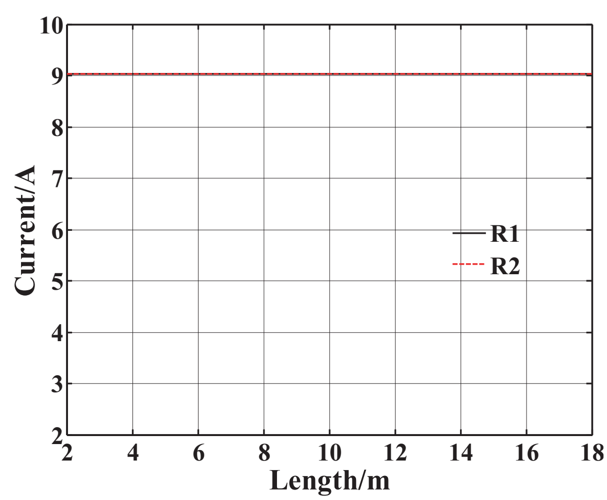

Figure 12. ECL for the loads R_1 and R_2 when the elevation angle θ, the azimuthal angle φ, and the polarized angle θ_E are 90°, 0°, and −90°, respectively.

3.4. Effects Induced by TVS When Cavity Exists or Not

A shielding cavity is added to the model to study the effects induced by the TVS when shielding cavity exists, as shown in Figure 13. The dimensions of the cavity are $2.4\,\mathrm{m} \times 1\,\mathrm{m} \times 0.5\,\mathrm{m}$. There are three slits with dimensions $0.5\,\mathrm{m} \times 0.2\,\mathrm{m}$ on the cavity. The TVS limiter is connected at end B. Other parameters are the same as those in Section 3.1.

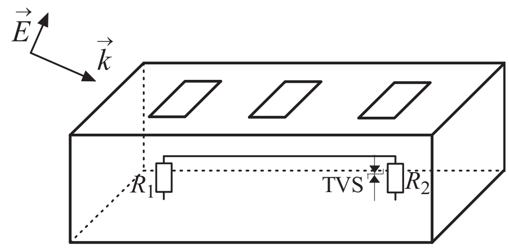

Figure 13. A simple model with a shielding cavity.

Figure 14 shows the current of R_1 changing with the electric field. Compared with the results without the cavity shown in Figure 6(a), the relation between the current and electric field is not linear any more. The reason for this is that the duration of the field inside the cavity is much longer than that of the incident EMP due to the resonance of the cavity. Figure 15 shows currents of the loads when the electric field is $10\,\mathrm{kV/m}$. It can seen from the results that the duration of the coupled current is much longer than that without the cavity. A longer duration leads to a larger ECL. As a result, in the case without the cavity, the relation is linear while in the case with the cavity, the relation turns into nonlinear. This implies that the existence of the cavity will increase the nonlinear effect of the TVS on the other end.

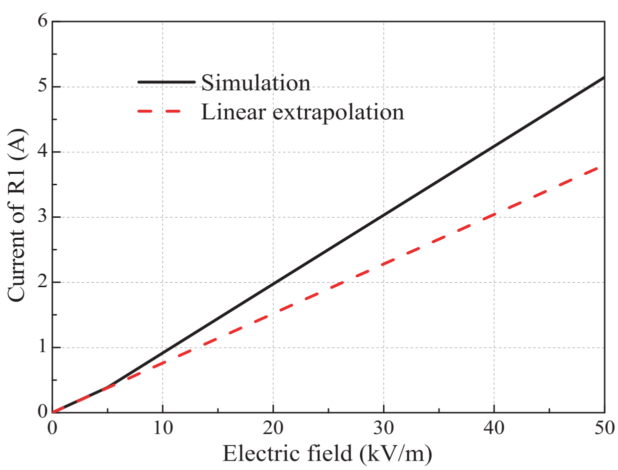

Figure 14. The current of R_1 versus incident electric field when there is a shielding cavity and the TVS limiter is connected at end B.

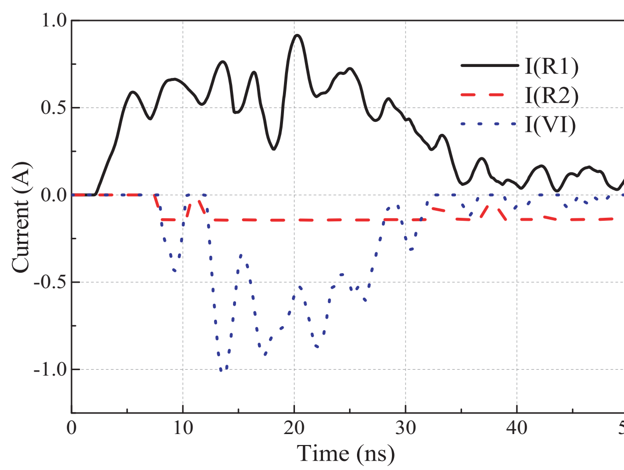

Figure 15. The currents of the loads for the case with a cavity when the electric field is $10\,\mathrm{kV/m}$.

4. DISCUSSION

According to above study, the TVS limiter not only protects the circuit which it intends to protect but also may introduce changes to the response of the other end which is connected with the protected circuit with a transmission line. The effect of the TVS limiter on the other end depends on many parameters, such as the incident direction of the HPEM pulse, line length, location of the TVS, and shielding cavity. The study shows that the effect will increase with the decrease of the line length, the addition of a shielding cavity, the increase of the electric field, and the decline of the coupling to the other end.

In the protection design of an electronic system, a low-level test will be carried out to get the responses of the entire system, and then the potentially susceptible circuit will be determined. Some measures, such as the TVS limiter, will be taken to protect the potentially susceptible circuit. According to this study, when a TVS limiter is applied to protect the potentially susceptible circuit, the effect of the TVS limiter on another end, which is connected to the susceptible circuit through a transmission line, should be carefully treated. A circuit at the other end, which is immune before the TVS limiter is added, may become susceptible when the TVS is connected to the system, and more design margin should be set. Due to nonlinear effects depending on the incident direction of the external HPEM pulse, different incident directions should be considered as many as possible in the real testing.

Unlike the electricstatic discharge (ESD), which is a local EMI source, the external HPEM pulses such as HEMP or LEMP can be considered as a plane-wave source for small electronic systems and couples with the entire systems. The nonlinear effects induced by the protection device on the entire systems should be considered. Compared with the case for HEMP, the nonlinear effect for LEMP may be larger because the width of LEMP is wider which will results in a larger ECL.

5. SUMMARY AND CONCLUSIONS

This paper studies the nonlinear effects induced by a TVS limiter on a simple system illuminated by an external HPEM pulse. The results show that the TVS limiter not only protects the circuit, which the TVS limiter is connected to, but also may affect the response of the other end which is connected to the circuit by a transmission line. The effect of the TVS limiter on the other end depends on the incident direction of the HPEM pulse, TVS location, line length, electric field level, and cavity. When the ECL of a load is longer than the line length, or its coupling with then external HPEM pulse is weaker than the other end, its response will be affected by the other end connected with a TVS limiter. The addition of a shielding cavity will increase the effect because the cavity will increase the duration of the field which results in a larger ECL.

Because the addition of a TVS limiter may increase the responses of the other end, special attentions, such as considering different incident directions as many as possible in the real testing and setting more margins, should be paid to the protection design.

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REFERENCES

1. Chuang, C. and M. Ker, "On-chip transient voltage suppressor integrated with silicon-based transceiver IC for system-level ESD protection," *IEEE Transactions on Industrial Electronics*, Vol. 61, No. 10, 5615–5621, 2014.
2. Chuang, C. and M. Ker, "System-level ESD protection for automotive electronics by co-design of TVS and CAN transceiver chips," *IEEE Transactions on Industrial Electronics*, Vol. 17, No. 3, 570–576, 2017.
3. Chen, W., X. Yang, and Z. Wang, "A novel hybrid common-mode EMI filter with active impedance multiplication," *IEEE Transactions on Industrial Electronics*, Vol. 58, No. 3, 1826–1834, 2011.
4. "Testing and measurement techniques-test methods for protective devices for HEMP and other radiated disturbances," *IEC6100-4-23*, 2000.
5. Fiori, F. and P. S. Crovetti, "Nonlinear effects of radio-frequency interference in operational amplifiers," *IEEE Trans. Circuits and Systems — I: Fundamental Theory and Applications*, Vol. 49, No. 3, 367–372, 2002.

6. Fiori, F. and P. S. Crovetti, "Prediction of the effects of EMI in CMOS operational amplifiers by a two-input volterra series model," *IEE Proceedings — Circuits, Devices and Systems*, Vol. 150, No. 3, 185–193, Jun. 2003.
7. Wunsch, D. C. and R. R. Bell, "Determination of threshold failure levels of semiconductor diodes and transistors due to pulse voltages," *IEEE Transactions on Nuclear Science*, Vol. 15, No. 6, 244–259, Feb. 1968.
8. Nitsch, D., M. Camp, F. Sabath, J. L. Haseborg, and H. Garbe, "Susceptibility of some electronic equipment to HPEM threats," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 46, No. 3, 380–389, Aug. 2004.
9. Hoad, R., N. J. Carter, D. Herke, and S. P. Watkins, "Trends in EM susceptibility of IT equipment," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 46, No. 3, 390–395, Aug. 2004.
10. Ren, Z., W. Y. Yin, Y. B. Shi, and Q. H. Liu, "Thermal accumulation effects on the transient temperature responses in LDMOSFETs under the impact of a periodic electromagnetic pulse," *IEEE Transactions on Electron Devices*, Vol. 75, No. 1, 345–352, Jan. 2010.
11. Zhou, L., S. Zhang, W. Yin, et al., "Investigation a thermal breakdown model and experiments on a silicon-based low-nose amplifier under high-power microwave pulses," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 58, No. 2, 487–493, 2016.
12. Picket-May, M., A. Taflove, and J. Baron, "FDTD modeling of digital signal propagation in 3-D circuits with passive and active loads," *IEEE Transactions on Microwave Theory and Technology*, Vol. 42, No. 8, 1514–1523, 1994.
13. Bayram, Y. and J. L. Volakis, "Hybrid S-parameters for transmission line networks with linear/nonlinear load terminations subject to arbitrary excitations," *IEEE Transactions on Microwave Theory and Technology*, Vol. 55, No. 5, 941–950, 2007.
14. Yan, H., L. Yan, X. Zhao, H. Zhou, and K.-M. Huang, "Analysis of electromagnetic field coupling to microstrip line connected with nonlinear components," *Progress In Electromagnetics Research B*, Vol. 51, 291–306, 2013.
15. Xie, H., J. Wang, and D. Sun, "Spice simulation and experimental study of transmission lines with TVSs excited by EMP," *Journal of Electromagnetic Waves and Applications*, Vol. 24, No. 2–3, 401–411, 2010.
16. Paul, C. R., *Analysis of Multiconductor Transmission Lines*, Wiley, New York, 1994.
17. Xie, H., J. Wang, J. Wang, et al., "A hybrid FDTD-SPICE method for transmission lines excited by a nonuniform incident wave," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 51, No. 3, 811–817, 2009.
18. Xie, H., T. Du, M. Zhang, et al., "Theoretical and experimental study of effective coupling length for transmission lines illuminated by HEMP," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 57, No. 6, 1529–1538, 2015.
19. Xie, H., Y, Li, H. Qiao, et al., "Empirical formula of effective coupling length for transmission lines illuminated by E1 HEMP," *IEEE Transactions on Electromagnetic Compatibility*, Vol. 58, No. 2, 581–587, 2016.