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Response Characteristics of Gas Discharge Tube to High-Power Microwave

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ABSTRACT Gas discharge tube (GDT), as an important protective device, has been developed and employed for the protection of circuit against high-power electromagnetic energy. Accurate description of the protective property of GDT is critical for its practical applications. However, under the excitation of high-power microwave (HPM), how the GDT will respond and whether the GDT can still exhibit protective performance remain unclear. Herein, the response characteristics of GDT to HPM were studied in this article. With the increment of excitation voltage, the response time of GDT decreases exponentially, and eventually reaching about 10 ns. The suppression ratio to HPM energy can attain 90%. The dynamic breakdown voltage and arc-mode voltage continuously increase as the excitation voltage is increased. Specifically, the arc-mode voltage nearly exhibits a linearly increasing trend. Moreover, the response property of GDT to HPM was simulated by using a PSpice model. The simulations are in good agreement with the experimental results, indicating the model can be used for predicting the behaviors of GDT under the excitation of HPM.

INDEX TERMS Response characteristics, gas discharge tube, high-power microwave, PSpice simulation.

I. INTRODUCTION

With the rapid development of electronic information technology and its emerging applications, growing attention has been paid to the extremely variable electromagnetic environment that is becoming more prominent and intense. High-intensity electromagnetic pulse, especially high-power microwave (HPM), poses a great threat to the electronic systems [1]–[5]. In the meanwhile, with the significantly improved integration and informatization, electronic apparatus comes at the price of an increased vulnerability, which is more prone to functional failure or even damage to electromagnetic attack. The electromagnetic energy can couple into the interior electronics of a system through both the front-door and back-door coupling, leading to malfunction or damage of electronic systems, and electromagnetic threats have been presented in several literatures or standards [5]–[7]. To ensure the survival of electronic systems against high-intensity electromagnetic pulse, using protective device to prevent or limit high-power electromagnetic energy on circuit is one of the best protection methods.

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Gas discharge tube (GDT), as a reliable and effective protection device, has been applied in a variety of fields such as radar, communication, power system and signaling circuit [8]–[10]. Because of the nonlinear property, the response characteristics of GDT significantly depend on the applied waveforms [11], [12]. As to the microsecond high-intensity electromagnetic pulse like lightning, related work has been studied for decades, mainly including theoretic analysis, numerical simulation and experimental investigation [11]–[15]. The protective performances of GDT towards rectangular pulse with different pulse widths were described by H. Li, Y. Naito, E. A. Maluckov and M. Pejović [16]–[19], and till very recently, W. A. Radasky reported the response characteristics of GDT to a double exponential pulse (3/25 ns (rise time/pulse width)) for the purpose of verifying its protection effectiveness towards E1 high-altitude electromagnetic pulse (HEMP) [20]. HPM, which is characterized by nanosecond or even picosecond rise time and high carrier frequency of gigahertz, is significantly different from lightning and HEMP [21]. However, almost no work has been made on the response characteristics of GDT to HPM, how the GDT will respond to HPM and whether the GDT can still exhibit protective performance under the excitation of HPM are illusive.

In this article, the response characteristics of GDT to HPM were investigated on a home-made measurement system. As the excitation voltage increases, the response of GDT becomes faster, eventually reaching ~ 10 ns. The dynamic breakdown voltage and arc-mode voltage are continuously increased, and the arc-mode voltage nearly exhibits a linearly increasing trend. The suppression capability of GDT to HPM energy can be as high as 90%. Moreover, the response property of GDT to HPM was simulated by the use of a PSpice model. The simulations match well with the experimental results, demonstrating the simulation model can be employed for the prediction of GDT's behaviors under the excitation of HPM. This research will also provide a powerful support for the design of protection device towards HPM.

II. EXPERIMENTAL SYSTEM AND RESULTS

A. MEASUREMENT SYSTEM

The response of GDT to HPM was tested on a home-made measurement system, as shown in Fig. 1(a). An L-band klystron microwave power amplifier with carrier frequency of 1.35 GHz is employed as the HPM excitation source. The HPM pulse is injected into the GDT through a dual directional coupler. The input, residual and reflected pulses are recorded by a digital oscilloscope. A GDT (model No. 2029-23-SM-RPLF), with the static breakdown voltage of 230 V, was purchased from Bourns. In order to reduce the inductance effect, the GDT was inserted into a low inductance protecting house (Diamond SP 3000) prior to HPM injection experiments. A typical normalized output waveform of the HPM excitation source is shown as Fig. 1(b). It is clear to see that the HPM pulse signal has an oscillating feature. It oscillates continuously in the entire pulse duration. Fig. 1(c) shows the positive envelope (1.35 GHz) of the normalized HPM pulse signal. The pulse width is 200 ns, and the input voltage of GDT can be easily tuned in the range of 240–1089 V. In the following, only the positive envelope of the HPM pulse signal is illustrated for simplicity.

B. TEST RESULTS

When electrical breakdown of GDT occurs, one can directly obtain the information by comparing the input and measured residual pulse waveforms. Moreover, once the protection performance of GDT is triggered, its initial state is varied, giving rise to impedance mismatch. As a result, the input HPM pulse is reflected back [20]. The residual and reflected signals are highly dependent on the input signal.

Since the static breakdown voltage is 230 V, the GDT doesn't break down till the applied HPM voltage reaching 240 V. The black curve in Fig. 2 shows the response of GDT at 240 V. In this case the GDT did trigger, but there is almost no reduction in the peak, and only a very small reflected signal is observed. As the input voltage is continuously increased to 519 V, the peak of the residual pulse is getting sharper and sharper, and simultaneously the pulse width and amplitude of reflected pulse is quickly increased. Further increment of

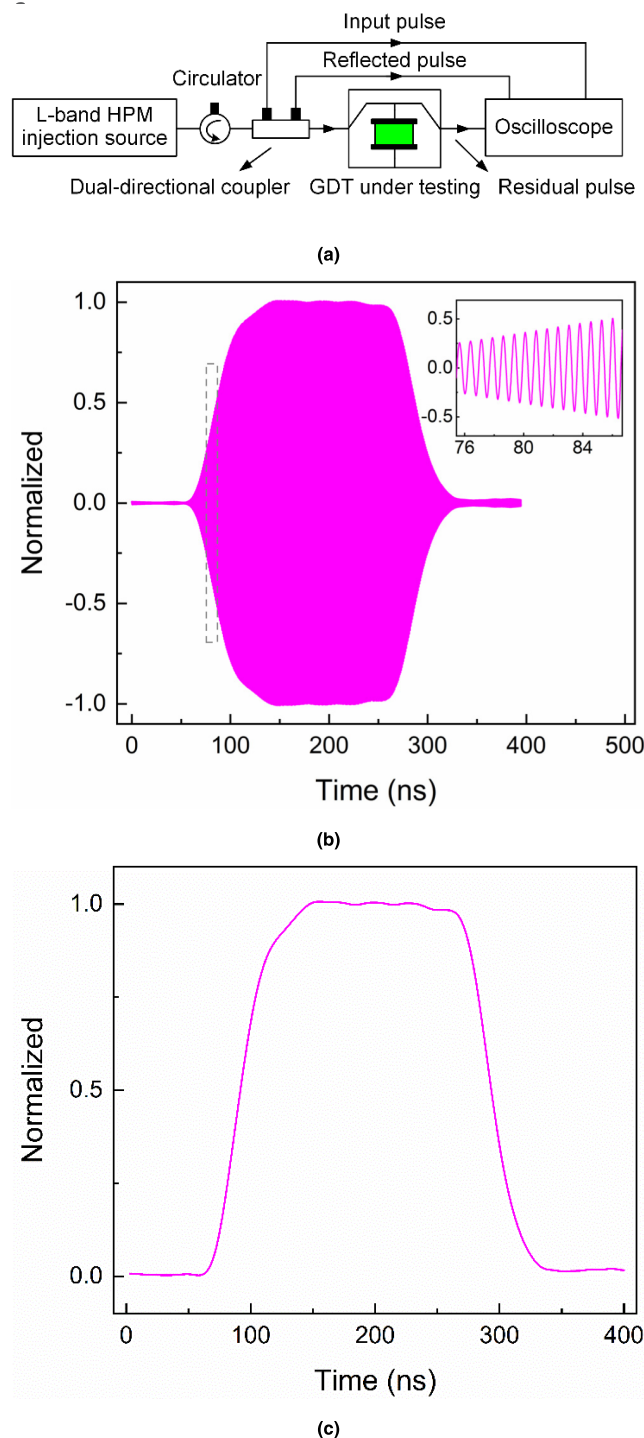


FIGURE 1. (a) Schematic illustrating the home-made system employed for the response characteristics measurement of GDT to HPM. (b) Typical normalized output waveform of the HPM excitation source. Inset: enlarged view of the waveform denoted by the rectangular dashed grey box. (c) Positive envelope of waveform illustrated in (b).

the input voltage gives rise to a much slower sharpening of the residual pulse peak, whereas the reflected signal quickly becomes larger. Specifically, for the cases with input voltage of more than 1000 V, the reflected signal is nearly identical to the input signal, except for a little difference in the

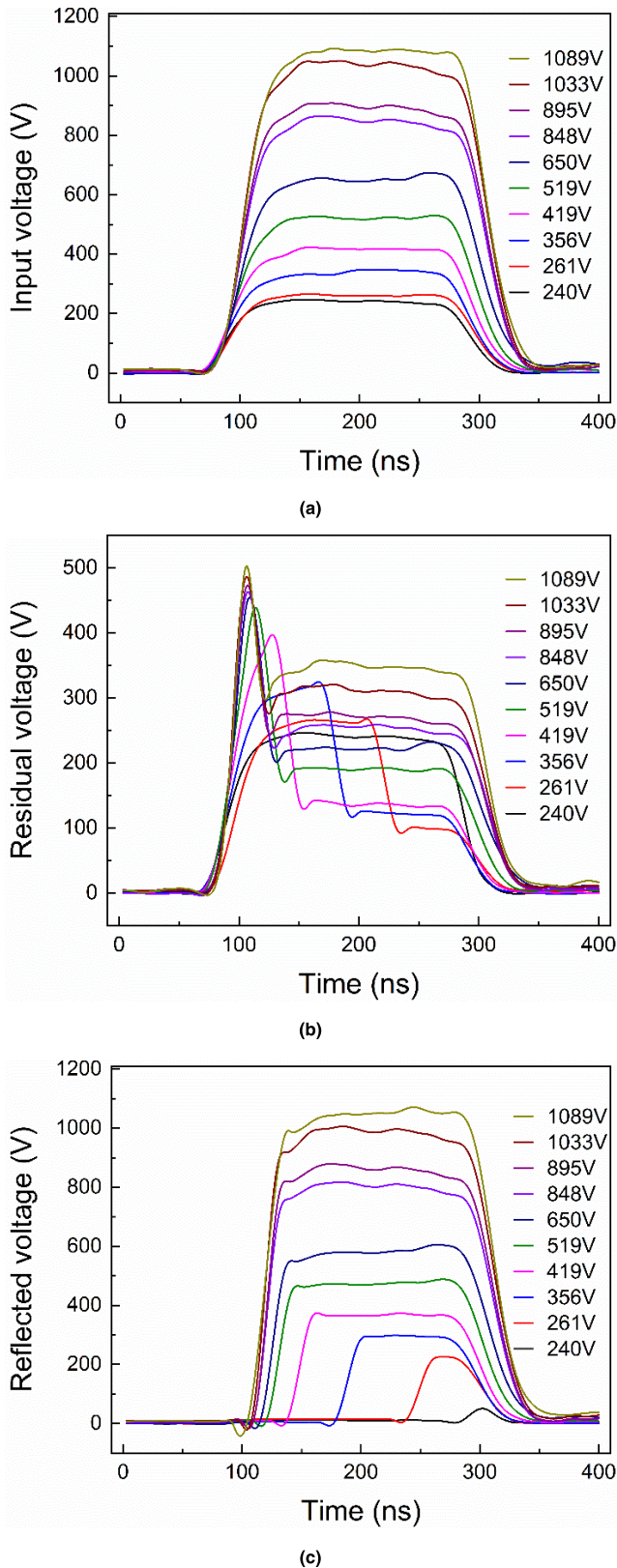


FIGURE 2. Measurement results. (a) Input HPM pulse, (b) Residual HPM pulse, and (c) Reflected HPM pulse.

pulse amplitude. In other words, most of the input energy is reflected back.

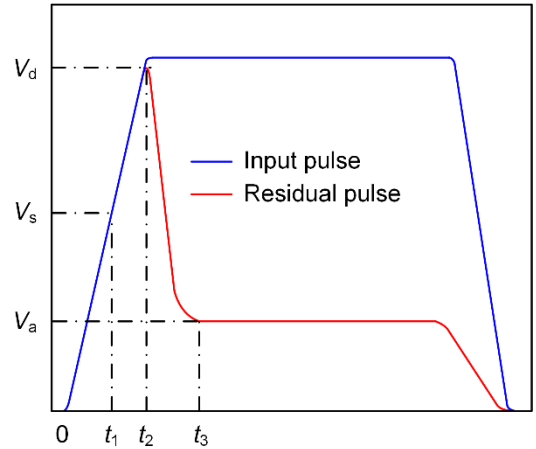
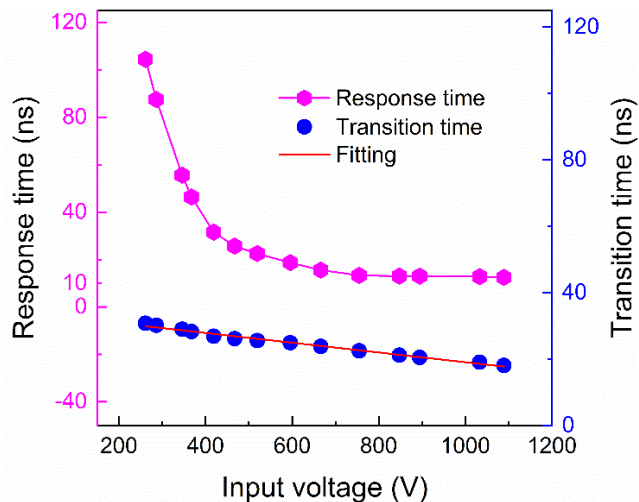


FIGURE 3. Schematic illustrating the protection parameters of GDT to high-intensity transient electromagnetic pulse [23].

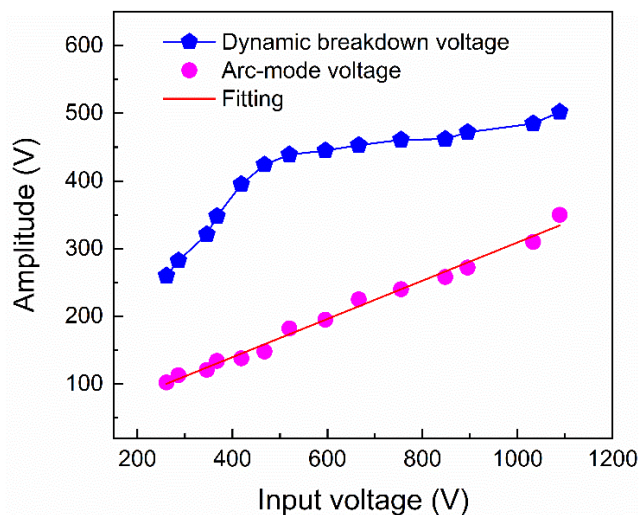
C. PROTECTION PERFORMANCE ASSESSING

In general, the protection performance of GDT against high-intensity transient electromagnetic pulse can be evaluated by parameters such as response time, transition time, dynamic breakdown voltage and arc-mode voltage. These parameters are detailedly described in Fig. 3. V_s , V_d and V_a represent the static breakdown voltage, dynamic breakdown voltage and arc-mode voltage, respectively. t_1 , t_2 and t_3 correspond to the time needed to reach these voltages. Before t_1 , the noble gas inside the GDT is considered to be insulated. As the applied voltage continues to increase, initial electrons begin to generate in noble gas, and the energy is gradually accumulated until a breakdown process occurs. The time interval between the application of a voltage equal to V_s and the appearance of a dynamic breakdown (V_d) is the electrical breakdown time delay, also called response time ($T_r = t_2 - t_1$) [22]. After such dynamic breakdown occurs, the time required for GDT to switch into the arc-mode state is the transition time ($T_t = t_3 - t_2$) [23].

The response time, transition time, dynamic breakdown voltage and arc-mode voltage were measured, and the correlations of these parameters with the input HPM voltage (V_{in}) are shown in Fig. 4. It is clear to see that the response time decreases exponentially with the increase of input voltage. When the input voltage exceeds 895 V, an almost stable response time of about 10 ns is obtained. Further increment of the input voltage can't give rise to a continuous reduction of the response time. There is a limit to the response time. Such an evolution of response time is probably ascribed to RF breakdown characteristics of noble gas in GDT [24]. In contrast, the transition time is not very sensitive to the input voltage, and decreases slowly in an approximately linear trend. Fig. 4(b) shows the evolutions of dynamic breakdown voltage and arc-mode voltage with the input voltage. Dynamic breakdown voltage, as an important indicator of gas breakdown property, increases quickly when the input voltage is less than 519 V. Then, the dynamic breakdown voltage is gradually increased and nearly saturates, indicating the



(a)



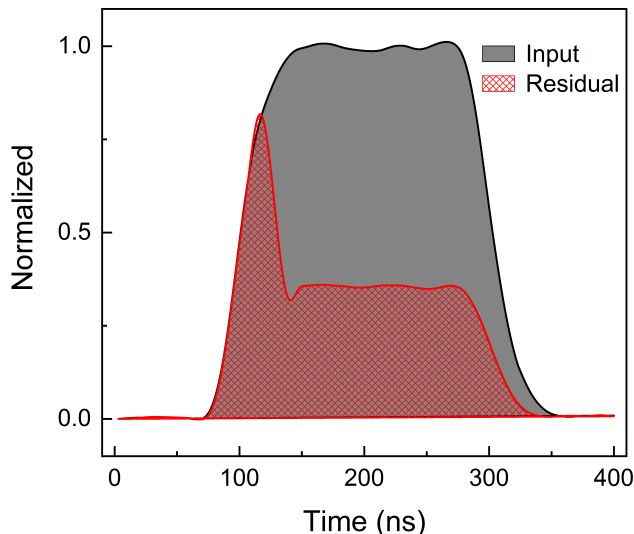
(b)

FIGURE 4. (a) Dependence of the response time and transition time on the input HPM voltage. The dependence of transition time on input HPM voltage is a linear fit ($T_r = -0.01V_{in} + 33.77$). The coefficients of determination for the fitting is $R^2 = 0.99$. (b) Evolution of the dynamic breakdown voltage and arc-mode voltage with the input HPM signal. The correlation between the arc-mode voltage and input HPM voltage is fitted linearly ($V_a = 0.28V_{in} + 26.59$). The coefficients of determination for the fitting is $R^2 = 0.99$.

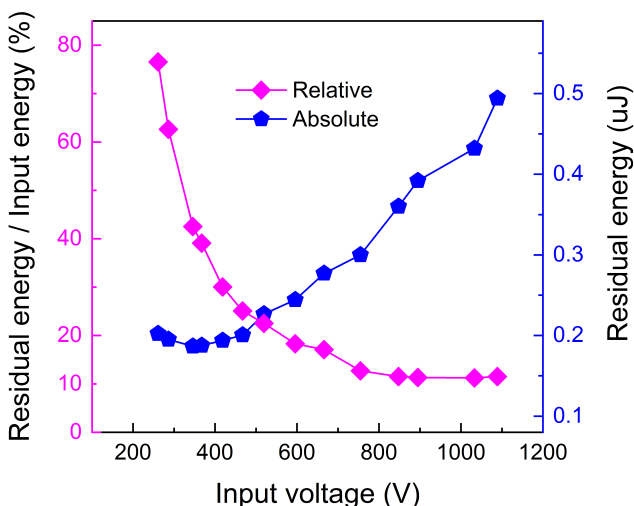
response characteristics of GDT to HPM satisfies electrical breakdown theory of gas. Once the GDT discharge process is established, its transmission and reflection voltages are determined by the impedance matching characteristics. That is, the arc-mode voltage is decided by the impedance of GDT in stable discharge stage. As a result, a linearly increasing trend is observed for the arc-mode voltage (Fig. 4(b)).

We further evaluate the protection performance of GDT to HPM from an energy perspective. The input and residual energy are schematically described as Fig. 5 (a), and calculated by using equation (1).

$$E = \int_{t_i}^{t_f} V^2(t) / R dt \quad (1)$$



(a)



(b)

FIGURE 5. (a) Definition of the input energy and residual energy, respectively. (b) Evolution of the residual energy with the input HPM signal.

where $V(t)$ is the amplitude of pulse signal, R is characteristic impedance.

It is clearly observed that the absolute residual energy is slightly decreased initially, and then continuously increases as the input HPM voltage becomes larger (Fig. 5(b)). Whereas, the percentage of residual energy to input energy is continuously decreased with the increase of input HPM pulse voltage to about 900 V. When the applied voltage exceeds 900 V, the ratio remains about 10% instead of decreasing. These results show that with the increase of input power, the suppression of HPM energy by GDT becomes more effective, and GDT can suppress nearly 90% of the input energy at most, demonstrating the GDT can be an outstanding suppressor of HPM.

Through the systematic investigations, typical response characteristics of GDT to HPM can be summarized as follows:

1) RESPONSE TIME

GDT can be triggered under the excitation of HPM, and its response time can reach 10 ns, which is only slightly slower than that of PIN limiter [25].

2) ARC-MODE VOLTAGE

Since the arc-mode voltage is mainly determined by the impedance characteristics of GDT, it is thus linearly increased as the input HPM voltage becomes larger.

3) ENERGY SUPPRESSION RATIO

The maximum suppression ratio of GDT to HPM energy is as high as 90%, indicating GDT can be an outstanding suppressor.

III. SIMULATION STUDIES

A. MODELING

Because the response characteristics of GDT to HPM still satisfy the electrical breakdown theory of gas, the simulation model developed by A. Larsson can thus be employed to reveal the response characteristics of GDT to HPM [26], [27]. However, owing to the oscillating characteristics of HPM pulse signal, an identical voltage value will appear repeatedly in the pulse duration (Fig. 1(b)). The time needed to reach the static breakdown voltage can't be solely and precisely determined. As a result, the model can't be used directly. In order to make the simulation stable, a detection circuit was introduced in our simulation model (Fig. 6(a)). The detection circuit that consists of matching resistance R' , rectifier diode D , charging/discharging capacitor C' , load resistance R'' and smoothing filter (L'' , C'') can retrieve the positive envelope of HPM pulse signal, thus converting the oscillating HPM pulse into a unipolar one (Fig. 6(b)). As a result, the simulation model proposed by us can be employed to simulate the response property of GDT to HPM. Two main discharge processes in the GDT were modeled. First, the response time, i.e., the time delay between the static breakdown voltage and the dynamic breakdown voltage; second, the time-dependent GDT resistance (dynamic breakdown to arc-mode transition phase and arc-discharge process).

R_1 , C_1 and L are the insulation resistance, capacitance and inductance of GDT, respectively. R_1 and C_1 are obtained from electrical characteristics datasheets of GDT provided by the Producer [26], [28], [29]; L is approximately determined by the formula $L \approx Kd$ (nH), where $13 < K < 17$, d is the gap distance of GDT [30], [31]. The three boxes, SC (Switch Control), RC (Resistance Control), and DC (Detection Circuit), include models of the GDT discharge characteristics.

The response time is modeled with the assistance of SC box and DC box. When the static breakdown voltage is attained, the response time can be obtained by using the empirical formula:

$$T_r = aS^{-b} \tag{2}$$

where S is the voltage steepness of wave front that is obtained from the excitation HPM signal [26], [29],

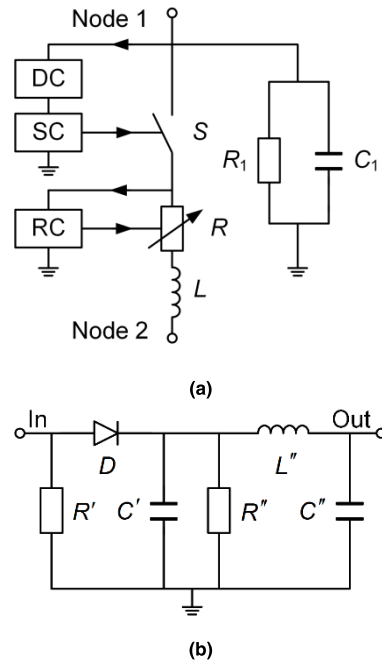


FIGURE 6. (a) Simulation model. (b) Detection circuit.

a and b are constants of GDT that are determined by measurements [26], [29]. When the response time has passed, the switch closes.

The time-dependent GDT resistance is modeled by using the RC box on the basis of different discharge processes. For the dynamic breakdown to arc-mode transition process, the Toepler formula $R = kd / (\int_0^t i(t) dt)$ is used. Where i is the current flowing in the GDT gap, d is the gap distance, and k is the empirical coefficient of the GDT employed.

We set $i(t) = |i(t)|$ in actual use of the Toepler formula, so as to avoid unreasonable oscillation of the resistance in the case of HPM. For the arc-discharge process, a constant resistance is employed.

B. SIMULATION RESULTS

In order to demonstrate the effectiveness of the simulation model of GDT proposed by us, we first built this model by using PSpice circuit simulation tool to reveal the response characteristics of GDT to HPM pulse with input voltage of 261 V. The simulated and measured residual voltages of GDT are shown in Fig. 7a. It is clear to see that the simulated residual signal is nearly the same to the measured one, indicating the simulation model developed by us can well reproduce the experiment. Moreover, the simulation model was utilized to simulate the residual signal of GDT with excitation voltage of 650 V. The simulated and the corresponding measured residual signals are displayed in Fig. 7b. The simulated and measured residual signals coincide with each other well. This result further confirms the PSpice simulation model can be employed to obtain the residual signal of GDT under the excitation of HPM.

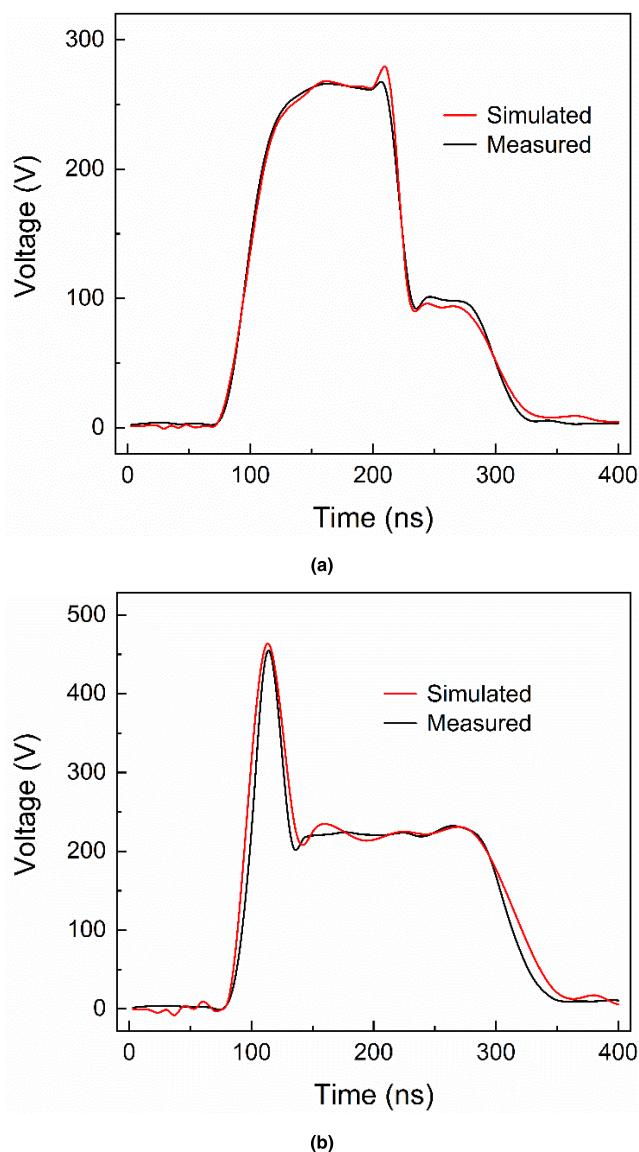


FIGURE 7. Simulated and measured residual signal of GDT under the excitation of HPM signal with different voltages. (a) 261 V, and (b) 650 V.

IV. CONCLUSION

In this work, the response property of GDT under the excitation of HPM was carefully investigated. As the injection voltage is increased, the response of GDT gets faster, finally attaining ~ 10 ns. The dynamic breakdown voltage and arc-mode voltage continuously increase as the excitation voltage is increased, and the arc-mode voltage nearly exhibits a linearly increasing trend. The suppression capacity of GDT to HPM energy can be as high as 90%. Moreover, a simulation model based on PSpice tool was built to reproduce the measured residual signal. The simulated residual signal matches well with the measured one, demonstrating the model can be employed for predicting the behaviors of GDT under the excitation of HPM. This research will also provide a powerful support for the design of protection device towards HPM.

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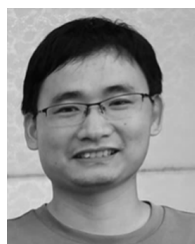
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