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RESEARCH

# Equivalent Circuit and Damage Threshold Study of Communication Interfaces under HEMP

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**Abstract**

In a strong electromagnetic pulse environment, high-intensity, broadband electromagnetic pulse energy is transmitted to the communication interface circuit through the interconnection cable, causing interference or damage to the internal electronic components and chips, and even posing a serious threat to the entire communication equipment. Based on the field line coupling model, the coupling effects of communication device interfaces under different terminal impedances are studied in this paper. By establishing the coupling circuit model of RS-232 interface under HEMP, and combining with pulse injection experiment, the equivalent circuit model of RS-232 interface is accurately determined, and the damage threshold of the sending end of RS-232 interface under HEMP is obtained. Compared with the measured data before and after the interface damage, the accuracy of the model and the reliability of the modeling method are verified, and the two agree well. The proposed interface equivalent circuit model can not only accurately characterize the coupling effect of communication equipment interface under the action of strong electromagnetic pulse, but also provide simulation level support for the subsequent design of communication equipment interface protection circuit. This method can be extended to different types of strong electromagnetic pulse and communication interfaces, and has a good application prospect.

**Keywords** Field line coupling · RS-232 interface · HEMP · Equivalent circuit model · Damage threshold

## 1 Introduction

With the integration of electronic communication systems, the wired communication interfaces on devices have become densely packed, resulting in increasingly complex electromagnetic effects on the interface circuits. Particularly, when communication equipment work in strong electromagnetic pulses, the energy released by the instantaneous discharge of electromagnetic pulses can be conducted through interconnect cables to the interface circuits, damages can be caused to the internal electronic components and chips of the interface circuits, resulting in system functionality disruptions, loss of control, or even system crashes [1]- [2]. To ensure normal operation of communication equipment under strong electromagnetic pulses, it is necessary to simulate and estimate the electromagnetic pulse coupling response and damage threshold of the communication interface circuit. According to the simulation and experiment results, the protection circuit is designed to protect the safety of communication equipment [3].

In recent years, many researches focused on electromagnetic pulse effect in computer and other communication systems. Bao Yongbo used XFDTD electromagnetic simulation to study the coupling effect of LEMP inside of portable computers [4], it can be showed that the influence of LEMP is directly related to the open hole area and adjacent holes will weaken the overall shielding efficiency. Yang Jie studied the impact of HPM on the computer host and display interface [5], the three-parameter Weibull function was adopted to find the damage threshold interval of the computer.Qiu Yang studied the transmission path of computer digital video interface [6], and built time-frequency domain models of serial and parallel transmission. Javad.Meiguni conducted a protective design for the damage and failure of USB connectors caused by electrostatic discharge [7], adopted the system Efficient electrostatic protection design

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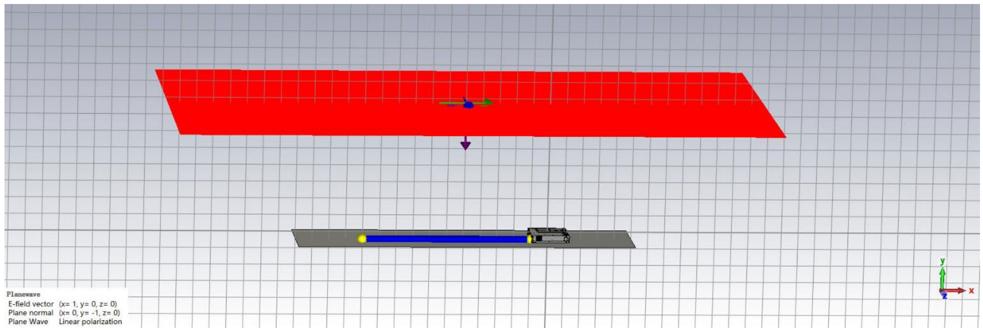



**Fig. 1** CST Coupling Model for Single Line Coupling in HEMP

(SEED) method to simulate the coupling current into the connector, and used TVS to design the protective circuit. I.S.Antyasov found the VGA interface can also intercept stray electromagnetic radiation when the VGA interface is closed [8], proving that the shielding performance of VGA interface is affected by the shielding material and structure, and also verifying the effect of VGA shielding combined with overvoltage and overcurrent protection technology.

As can be seen above, the main research on the coupling effect to computer interfaces focused on static electricity and LEMP pulse, and the research on HEMP is very few. Compared with static electricity and LEMP, HEMP is more destructive and has a larger interference range. In addition, there is a lack of analysis and summary of the coupling path and coupling law of the computer interface under HEMP irradiation. Therefore, Hemp-coupled analysis of computer interfaces becomes necessary.

Due to the diversity of communication interfaces, different interfaces have different transmission rates, signal propagation modes, and coding modes. It can be exposed to different types of strong electromagnetic irradiation.It is chosen the RS-232 communication interface as the sensitive circuit and HEMP(High Altitude Nuclear Electmagnetic Pulse) as the typical source of strong electromagnetic pulse excitation in this paper. An equivalent circuit model and damage threshold analysis under real injection test conditions are developed. This method can provide effective guidance for the subsequent protection circuit design and can be extended to other interfaces and strong electromagnetic pulse excitation environments.

## 2 Hemp Coupled Modeling of a Typical Communication Interface Circuit

### 2.1 HEMP Coupled Current Analysis Based on Field-Line Coupling Simulation

After a high-altitude nuclear explosion, nuclear weapons generate an extremely intense HEMP radiation field in space, extending to the vicinity of communication devices and cables. Due to the good shielding performance of communication equipment, the HEMP radiation field primarily influences the communication cables through field line coupling. According to IEC 61000-2-9 standards, the rise time of HEMP irradiation waveform is 2.5 ± 0.5ns, and the half-height width is 23 ± 5ns. The magnitude of the HEMP coupling current in communication cables directly determines whether the interface circuit will be disturbed or damaged [9, 10].

**Table 1** Coupled Current Of Transmission Lines At Different Impedance Ends Under HEMP Radiation.

| Terminal Impedance (Ω) | Peak current of HEMP coupling (A) |
|---|---|
| 1 | 7.06 |
| 5 | 6.92 |
| 10 | 6.75 |
| 25 | 6.29 |
| 50 | 5.65 |
| 100 | 4.7 |
| 200 | 3.52 |
| 500 | 2.01 |

The coupling characteristics of HEMP on communication cables can be studied using a field-wire coupling model, as shown in Fig. 1. It has been discovered that the magnitude of the HEMP coupling current is influenced by the termination impedance at both ends of the communication cable, the actual impedance of the HEMP coupling circuit may not be 50Ω mostly. It also can be affected by the length of the cable, its radius, the height above the ground, and the incident angle of the HEMP radiation field.

In the simulations, the HEMP radiation field is radiated vertically to the transmission line, with a cable length of 5 m. The height from the ground is set to 10 mm to reflect the actual communication equipment. The cable radius is set to 0.5 mm, based on commonly used. The coupled current in the transmission line under HEMP radiation is obtained, and its peak value with the different terminal impedance are shown in Table 1.

It can be observed that as the impedance at both ends of the transmission line increases, the peak value of the HEMP coupling current decreases, and a current variation can cause interference or damage to the interface circuit.

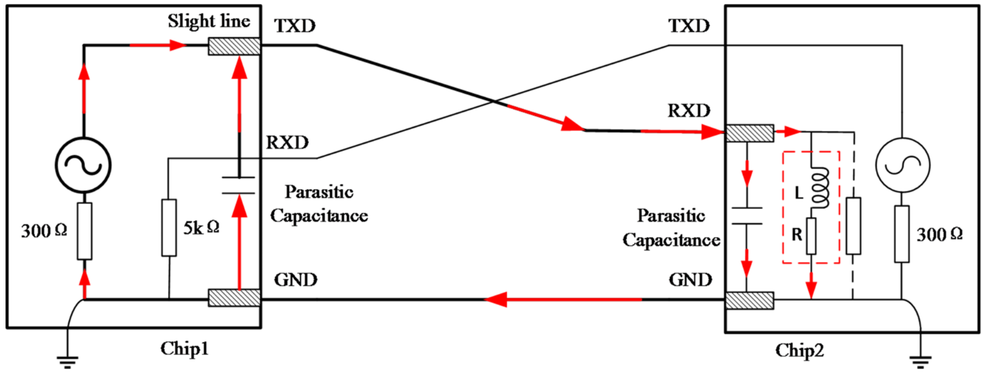



**Fig. 2** Signal loop model of RS-232 interface circuit with strong electromagnetic pulse coupling

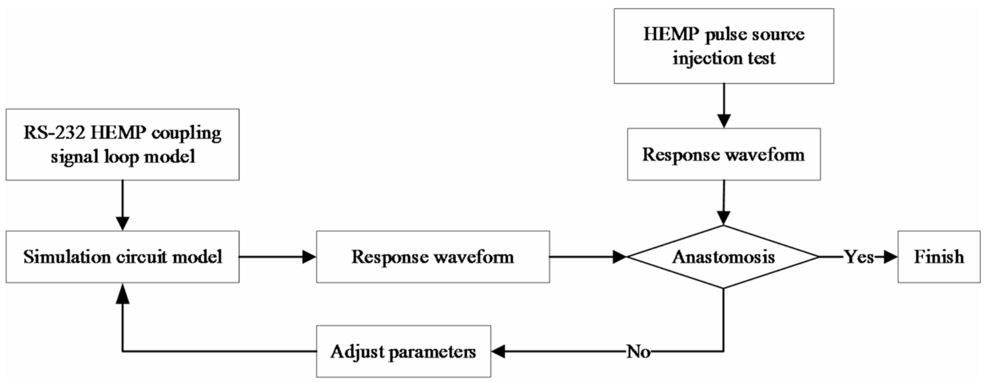



**Fig. 3** Research scheme of impedance characteristics of RS-232 interface

## 2.2 Modeling of HEMP Coupled Signal Loop of the Interface Circuit

To get the equivalent circuit of communication interface accurately, the HEMP coupled signal loop is built first in Fig. 2. Parasitic impedance between the microstrip line and ground in the interface circuit mainly reflects the distributed capacitance to the ground, which is about tens of pF. Due to the rise time of the HEMP coupling current signal being in the ns range and the spectrum components mainly distributed within 200 MHz, the high-frequency components inevitably result in the high-frequency impedance of the microstrip line to ground is much smaller than the termination impedance of the normal signal loop [11].

According to Kirchhoff law, HEMP-coupled currents are divided into different paths based on impedance. Therefore, the majority of HEMP coupling current signals are discharged along the loop composed of the signal line, parasitic capacitance, and ground, while a small portion of the current is discharged through the normal signal loop formed by the internal resistance and ground [12]. It is necessary to combine simulation modeling and experiments to obtain the equivalent impedance of the HEMP-coupled interface circuit which can be better used for subsequent damage analysis.

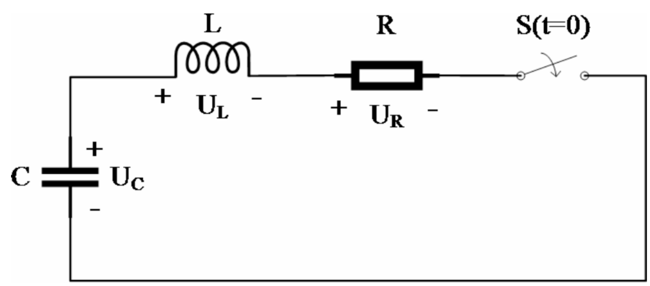



**Fig. 4** Equivalent Circuit Model of HEMP Pulse Injection Source

# 3 Equivalent Circuit Modeling of Rs-232 Interface

To establish an equivalent circuit model for the RS-232 interface circuit used to evaluate the interface damage threshold, the procedure based on HEMP injection test can be shown in Fig. 3. Parameters are adjusted to make the simulated response current waveform consistent with the HEMP pulse injection test, thus obtaining the equivalent impedance of the HEMP coupled loop when the interface circuit is working normally. First, the equivalent circuit of the HEMP pulse source needs to be established to complete the co-simulation subsequently.

**Fig. 5** Experimental platform of HEMP pulse source calibration test circuit

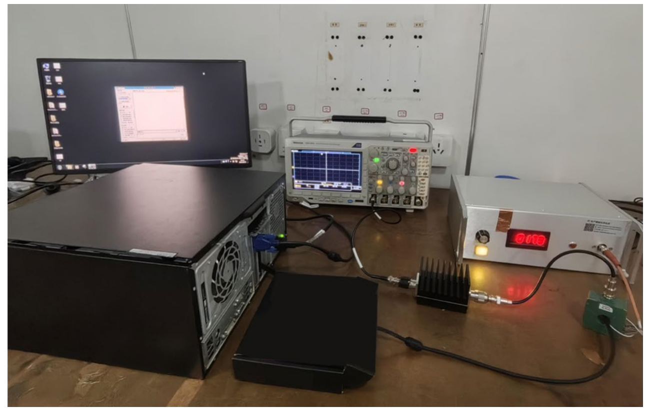


**Fig. 6** RS-232 interface circuit direct injection test

**Table 2** Key Parameters Of Experimental Waveform Under Different Injections.

| Calibration type | Injection voltage (V) | Peak value (A) | Rise Time (ns) | FHWM (ns) |
|---|---|---|---|---|
| Short circuit | 100 | 1.89 | 36.8 | 519.6 |
| | 300 | 5.62 | 37.6 | 516 |
| | 500 | 9.16 | 37.0 | 515.2 |
| 50Ω load | 100 | 0.96 | 27.2 | 986.6 |
| | 300 | 2.90 | 27.6 | 1000.7 |
| | 500 | 4.7 | 27.6 | 1026.6 |
| 10Ω load | 100 | 1.57 | 36.4 | 617 |
| | 300 | 4.54 | 38.8 | 635.8 |
| | 500 | 7.64 | 37.2 | 630.4 |

**Table 3** Comparison of HEMP Source Simulation Model With Measured Data.

| Calibration type | Injection voltage (V) | Peak value (A) | Rise Time (ns) | FHWM (ns) | Comparison |
|---|---|---|---|---|---|
| Short circuit | 100 | 1.89 | 36.8 | 519.6 | Actual measurement |
| | 100 | 1.83 | 39.1 | 541.8 | Simulation |
| 50Ω load | 100 | 0.96 | 27.2 | 986.6 | Actual measurement |
| | 100 | 0.97 | 25.7 | 1014.2 | Simulation |
| 10Ω load | 100 | 1.57 | 36.4 | 617 | Actual measurement |
| | 100 | 1.58 | 35.2 | 634.1 | Simulation |

### 3.1 Simulation Modeling of HEMP Injection Source

The pulse source model is built according to the actual circuit inside the HEMP pulse source. The equivalent circuit model for HEMP is established as shown in Fig. 4. C represents the charging and discharging capacitance, L represents the stray inductance generated by wiring, switches, and other components within the pulse injection source, and R represents the internal resistance of the pulse injection source [13].

The HEMP pulse source circuit calibration test is shown in Fig. 5. The direct injection response currents of the HEMP pulse injection source with short circuit, 50Ω, 10Ω three types of loads are obtained by the current caliper. Rise time and full width at half maximum (FHWM) are measured, and the test results are shown in Table 2.

By comparing the injection response waveform parameters with the simulation response waveform parameters, the device parameters of the circuit model are adjusted to make the simulation waveform gradually close to the test waveform. Finally, the parameters of each device in the equivalent circuit of the HEMP pulse injection source are determined with the capacitance C = 14nF, the resistance $R$ = 52Ω and the inductance L = 450nH.The parameter comparison of the simulation response waveform and test response waveform is shown in Table 3. By comparing the simulation results with measured data for the peak, rise time, and half-high-width, it can be seen that the simulation modeling and parameter settings of the HEMP source are accurate, and the established simulation model can be used to represent the HEMP source.

### 3.2 Acquisition of Interface Circuit Impedance Characteristics

As shown in Fig. 6, a direct injection test is conducted on the RS-232 interface board loaded on the communication equipment while it is in normal working condition. The waveform of the interface circuit under HEMP pulse is obtained through experiments, and interface equivalent impedance is extracted. The HEMP pulse current is directly injected into the data transmission core wire of the board, and the response current is monitored through an oscilloscope and the current caliper. A combined simulation is conducted to establish the HEMP source model and the interface circuit HEMP coupling loop impedance model.

First, direct injection experiments are conducted on RS-232 interface cards in the sending state loaded on the communication equipment, pulse current is directly injected into the TXD line of the RS-232 cable, and the response current on the TXD data transmission core line of the card is monitored using an oscilloscope and a clamp meter. The response waveform parameters obtained from the direct injection experiments on the RS-232 interface cards are shown in Table 4 below, with a clamp meter factor of 1 and a 20dB attenuator connected to the front end of the oscilloscope.

By utilizing the RS-232 interface circuit HEMP coupling loop model established before, an impedance equivalent circuit model is constructed. However, the final equivalent impedance circuit model requires continuous adjustment of the distributed capacitance and the impedance of the subsequent shunt circuit.

The tuning process of the RS-232 interface impedance equivalent circuit is similar to that of the pulse injection source circuit, as shown in Fig. 7. The distributed capacitance mainly causes the oscillation of the rising edge of the response current waveform, which affects the peak value and peak time in a small range.

**Table 4** RS-232 Interface Circuit Response Waveform Parameter.

| Injection voltage (V) | Peak value (A) | Rise Time (ns) | FHWM (ns) |
|---|---|---|---|
| 100 | 1.65 | 88.8 | 612.6 |
| 200 | 3.34 | 81.6 | 604.8 |
| 300 | 4.94 | 83.2 | 616.6 |

The final RS-232 interface impedance equivalent circuit obtained is shown in Fig. 8, with a distributed capacitance C = 15pF, resistance $R=4\Omega$, and inductance L = 775nH. The comparison table of simulation waveform parameters and test waveform parameters is shown in Table 5.

In Table 5, the error between the peak value, rise time, and half-height width of the simulation waveform and the test results is small, and the simulation model established can be used as equivalent circuit for RS-232 interface.

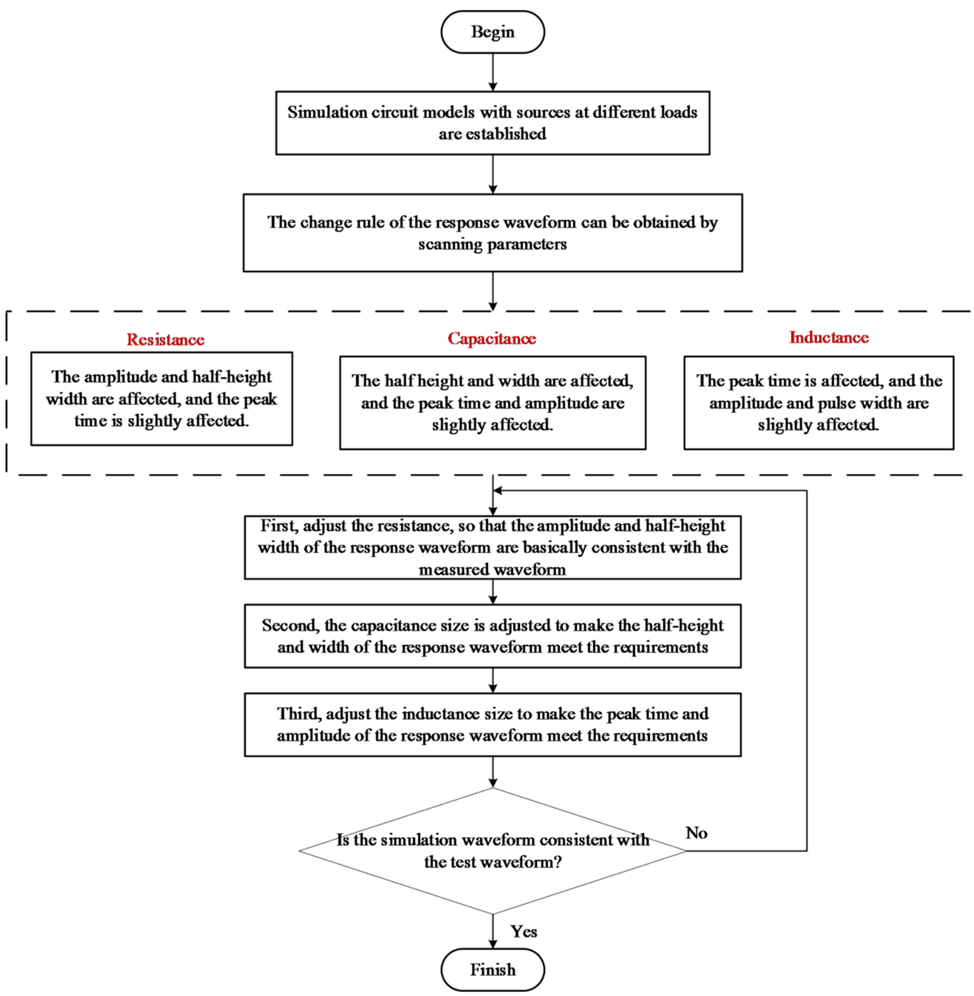



**Fig. 7** RS-232 impedance equivalent circuit parameter extraction

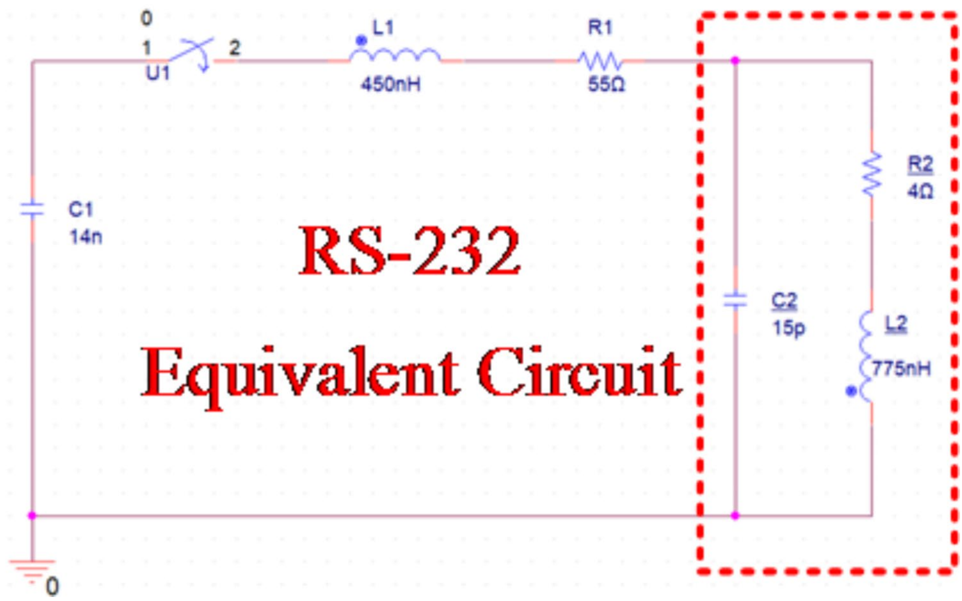



**Fig. 8** Equivalent impedance simulation circuit of RS-232 interface

**Table 5** Measurement and Simulation Results Comparison of RS-232 Interface.

| Injecting voltage (V) | Peak value (A) | Rise Time (ns) | FHWM (ns) | Comparison |
|---|---|---|---|---|
| 100 | 1.65 | 88.8 | 612.6 | Actual measurement |
| | 1.67 | 81.4 | 610.7 | Simulation |
| 200 | 3.34 | 81.6 | 604.8 | Actual measurement |
| | 3.33 | 81.4 | 613.0 | Simulation |
| 300 | 4.94 | 83.2 | 616.6 | Actual measurement |
| | 5.00 | 81.4 | 611.9 | Simulation |

### 3.3 Research on Distribution Parameters

Currently, the selected placement position of the interface circuit board in the experimental test is horizontal. However, under the ground bar of the test platform, there may be an influence on the distributed parameters to the ground [11]. In addition, the actual placement position of the interface circuit board in the chassis under real conditions may vary. In order to verify whether there is interference in the response waveform under different placement positions and different ground heights, the RS-232 interface circuit board is taken as an example and the HEMP pulse injection test is conducted under the condition of vertical placement.

In Fig. 9, the blue line represents the test waveform under horizontal placement, and the orange line represents the test waveform under vertical placement. By comparison, it can be seen that under both horizontal and vertical placement conditions, the waveform is basically the same. Therefore, it can be considered that the distribution parameters have no significant influence on the ground during the horizontal arrangement.

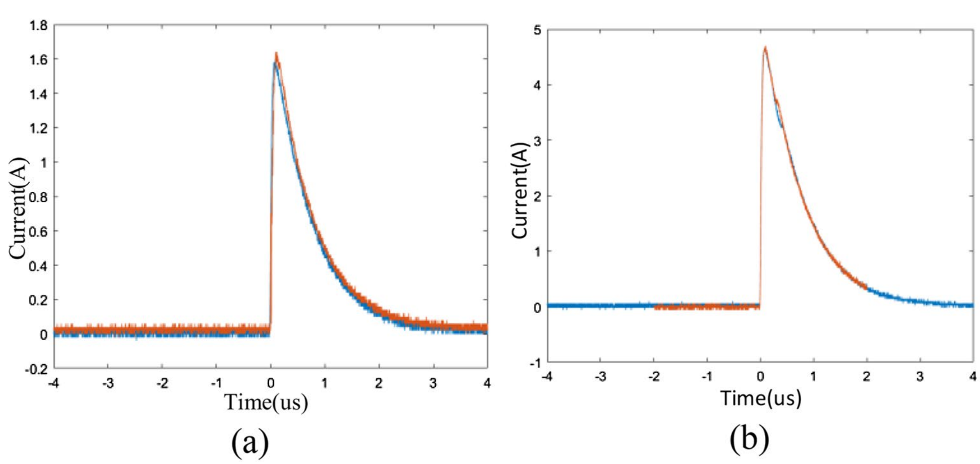



**Fig. 9** Horizontal placement (blue) and vertical placement (orange) response waveform comparison. (**a**)100 V Injection. (**b**) 300 V Inject

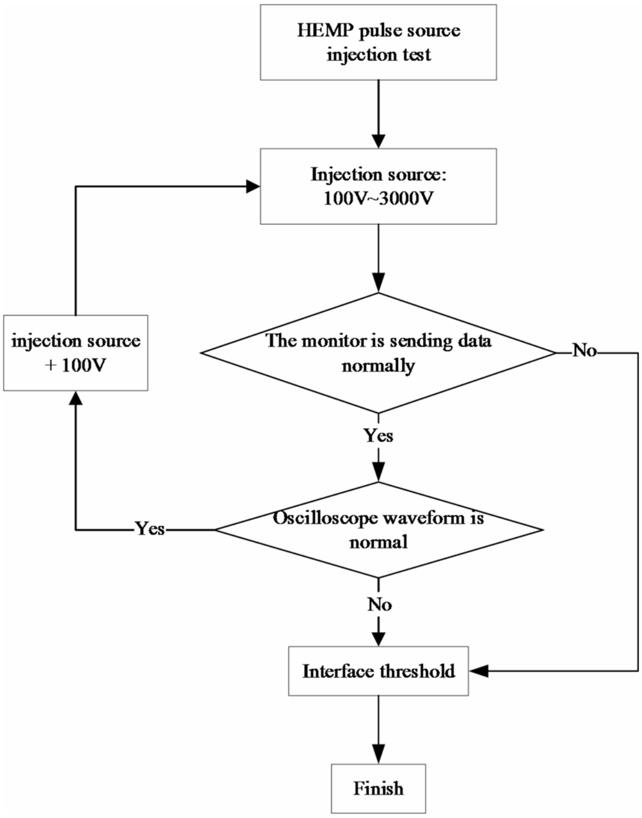



**Fig. 10** Threshold test scheme of RS-232 interface

## 4 Research on Damage Threshold of Rs-232 Interface Circuit

### 4.1 RS-232 Interface Circuit Damage Threshold Test

RS-232 enables full-duplex serial asynchronous communication using the unbalanced transmission. Data are transmitted unidirectionally by defining separate lines for transmission and reception [14, 15]. To obtain the damage threshold of the RS-232 interface circuit, smaller step increments of the HEMP injection source are adopted. The integrity of the interface circuit is observed by examining the waveform of the voltage acquisition card and the coupled current waveform of the HEMP pulse source. The experimental setup is similar to the impedance characteristic injection test of the interface circuit established in the previous section, and the experimental steps are shown in Fig. 10.

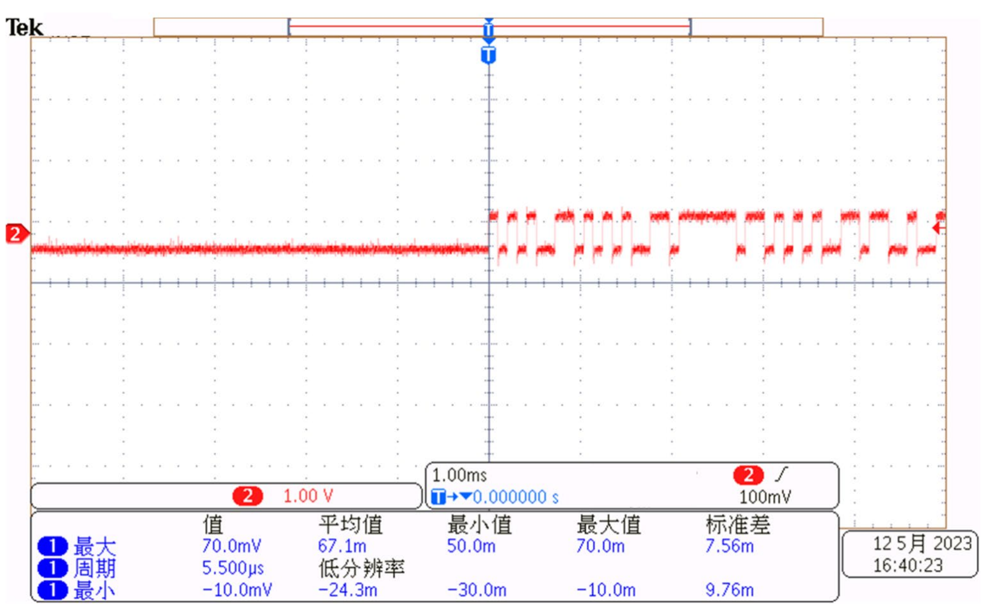
The communication equipment host built-in serial port debugging software controls the RS-232 interface circuit continuously send data in a loop. The Baud rate is set to 9600Baud, and it sends 0×55, 0×56, and 0×57 (corresponding to binary 01010101, 01010110, and 01010111) continuously with a period of 100ms. The RS-232 interface circuit board at the transmitting end is connected to an oscilloscope, which displays the waveform of the signal elements obtained through the voltage acquisition circuit, as shown in Fig. 11.

The injection voltage level of the HEMP pulse injection source starts at a minimum of 100 V and goes up to a maximum injection voltage level of 3 kV, with a minimum step size of 100 V. The performance changes of the interface circuit board are observed by gradually increasing the injection voltage.

### 4.2 Applicability of the Simulation Model Near the Threshold

Through experiments, it can be discovered that when the voltage reaches around 1200 V, the RS-232 interface circuit board becomes damaged and the damage threshold is about 18.7 A. To study the applicability of the interface circuit

**Fig. 11** Normal element waveform of voltage acquisition board



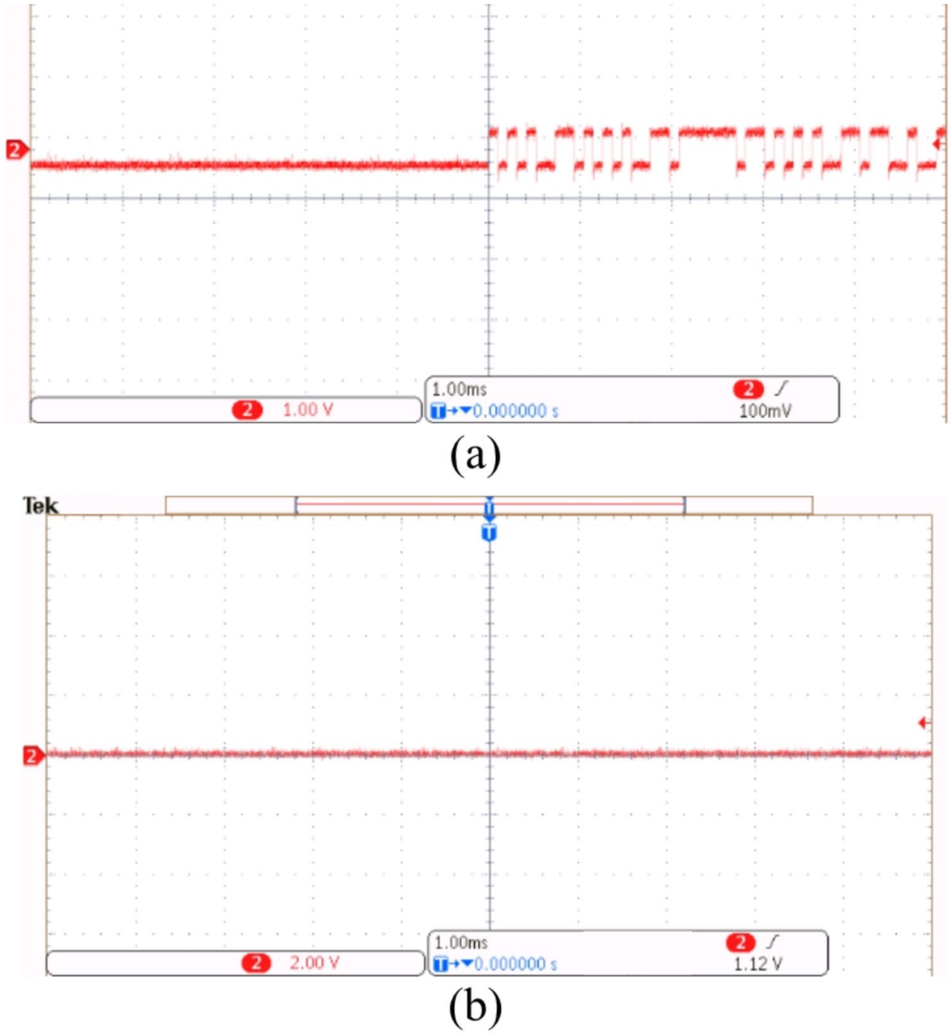



**Fig. 12** Signal element waveform when the voltage injection level is 1100 V, 1200 V. (**a**) 1100 V injection. (**b**) 1200 V Inject

**Table 6** Measurement and Simulation Results of RS-232 Interface Board (After Damage).

| Injecting voltage (V) | Peak value (A) | Rise Time (ns) | FHWM (ns) | Comparison |
|---|---|---|---|---|
| 1100 | 16.9 | 75.2 | 624.4 | Actual measurement |
| | 18.2 | 78.9 | 612.5 | Simulation |
| 1200 | 19.1 | 84.8 | 630.4 | Actual measurement |
| | 19.8 | 78.9 | 615.4 | Simulation |
| 1300 | 20.8 | 82.4 | 624.8 | Actual measurement |
| | 21.5 | 78.9 | 618.3 | Simulation |
| 2000 | 32.6 | 79.2 | 637.6 | Actual measurement |
| | 33.2 | 79.3 | 618.6 | Simulation |
| 2500 | 42.6 | 65.6 | 601.6 | Actual measurement |
| | 41.6 | 69.5 | 607.0 | Simulation |

equivalent impedance model established after the damage, the response waveforms under higher HEMP pulse injection levels are compared with the simulation results to determine if they are consistent. After testing the response waveforms at higher injection levels, whether the normal state interface equivalent impedance model applies to higher injection levels is determined.

A comparative analysis is conducted on the response waveforms of the interface circuit board after damage. The pulse-coupled current waveforms are obtained at five injection levels: 1100 V, 1200 V, 1300 V, 2000 V, and 2500 V, to verify the applicability of the simulated interface equivalent circuit model at higher injection levels. The results of the simulated waveform parameters and the test waveform parameters are presented in Table 6.

It can be seen from Table 6 that the RS-232 interface circuit simulation model established near the interface card damage threshold and after the damage is close to the measured coupling value, which verifies the applicability of the RS-232 interface circuit model before and after the damage.

### 4.3 Statistical Analysis of the Damage Threshold

Since the system is a HEMP injected RS-232 communication system, the computer needs to be connected to two ends

**Table 7** Coupling analysis of multiple measurements.

| | Voltage of HEMP signal source /V | Current at transmitter/A | Current at receiver /A |
|---|---|---|---|
| 1 | 1800 | 9.9 | 11.6 |
| 2 | 1700 | 9.7 | 10.4 |
| 3 | 1800 | 9.9 | 11.0 |
| 4 | 1700 | 9.5 | 10.6 |
| 5 | 1600 | 9.1 | 10.0 |
| 6 | 1700 | 9.5 | 9.8 |
| 7 | 1900 | 10.7 | 9.8 |
| 8 | 1800 | 10.1 | 9.4 |

of the board for communication. It is based on whether the system can continue to communicate normally.The system is more sensitive, so the double-ended damage threshold current is smaller than that of the single-ended damage threshold current (Table 7).

After 8 experiments of HEMP injection RS-232 communication system, the experiment shows that the communication system stops transmitting data when the current is about 9.5 A, and the average current is 9.6 A and the standard error is 0.28. Combining the pin diagram of the chip and the circuit test, it is inferred that the inverter has a break fault. Detailed sectional analysis will be performed in the future.

## 5 Conclusion

High-intensity, wide-bandwidth pulse energy released by HEMP will be conducted through interconnecting cables between communication devices and transmitted to the interface circuits directly connected to them, resulting in disturbance or damage to the internal electronic components and chips of the interface circuits, leading to abnormal operation of the communication system. It is crucial to reinforce and protect the interfaces to ensure the normal operation of the communication system under the influence of HEMP.

Among them, the key to protection is to simulate and estimate the coupling response of strong electromagnetic pulse in the interface circuit of communication equipment and obtain the fault threshold of the interface circuit accurately. This paper uses a typical communication interface circuit RS-232 as the research object. Through theoretical analysis, modeling simulation, and experimental test, a HEMP coupled signal loop model is proposed and the equivalent impedance of the loop is obtained. Based on the experimental results, the accuracy of the equivalent impedance model of the boundary interface is improved by parameter adjustment. The damage threshold of the RS-232 interface transmitter is obtained effectively through the experimental platform. The proposed interface equivalent model not only helps us to study the coupling effect under HEMP but also provides simulation-level support for the subsequent protection design against the damage threshold. This modeling method based on test is universal and can be extended to different strong electromagnetic pulses and different interface circuits. A more in-depth discussion of the physical damage mechanisms and how they relate to the observed thresholds will be the focus of subsequent research.

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**Data Availability** This article contains test data, which can be provided on request.

### Declarations

**Competing Interests** The authors have no competing interests to declare that are relevant to the content of this article.

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