Electromagnetic Pulse Threats to Electronic Information System and Corresponding Protection Measures

Sheng-quan Zheng[12] Dong-yun Hou[12] Qi-feng Liu[12] Feng Deng[12]
Science and Technology on Electromagnetic Compatibility Laboratory1
China ship development and design center2
Wuhan, China
E-mail zhengshengquan@hotmail.com

Abstract—**Electromagnetic pulse (EMP) radiation shall seriously disturb electronic information system. The EMP energy coupled from different approaches can even destroy semiconductor elements inside the equipment， make the system to function improperly. Several expressions of minatory EMP are investigated in this paper. The coupling characteristics and threat mechanism of EMP radiation entering into electronic information system are analyzed, and the EMP protection design methods for electronic information system are proposed in this paper.**

Keywords: electromagnetic pulse, coupling, threat, protection

I. INTRODUCTION

With the developing of the micro-electronic technology at very fast speed, the high integrated chips have greatly improved the information disposal rate, accuracy, secrecy, reliability and miniaturization. It makes the functions of command, control, communication, computer, intelligence, surveillance and reconnaissance (C4ISR) system more powerful. On the other hand, the C4ISR systems which based on the micro-electronic technology are facing a common challenge of the increasing high power electromagnetic environment destructibility, and easily be disturbed even destroyed by the exoteric high electromagnetic field. Therefore, various of EMP weapons, especially the short pulse and high power electromagnetic pulse weapon which have the pulse width in nanoseconds even in picoseconds have made great progress. These weapons can badly destroy the electronic information system by powerful EMP. The EMP radiation enters into the sensitive electronic equipments via types of path, disturbs or destroys different types of semiconductor elements and integrative circuits, makes the C4ISR system cannot work normally. Consequently, EMP protection requirement for electronic information system increasingly stand out.

EMP protection is a system engineering which should evaluate the threats from all paths through which EMP enters into the sensitive system according to the system mission and structural characteristic. The system protection project aimed at protection object and protection target should be constituted, which including protection design, element selection, special protection module, protection material and art and crafts. All protection measures should be test after implementation to ensure that specified performance characteristics have been met. Preventive maintenance and corrective maintenance on the EMP protection measures should be implemented through the system life cycle. In this paper, the EMP threat mechanism on electronic information system and its normal protection methods are discussed.

II. SEVERAL TYPES OF THREATENING EMP

There are many types of EMP, except lightning EMP and static discharge and pulse generated by radar and electric war, as EMP weapon which threatening the electronic equipments includes high-altitude electromagnetic pulse (HEMP), ultra-wideband (UWB) and narrow-band high power microwave (HPM).

A. A High-altitude electromagnetic pulse

HEMP is produced by the γ race which released from a nuclear explosion outside the earth's atmosphere acting with the atmosphere molecule. HEMP has a powerful peak electromagnetic field up to tens of V/m and wide effect area over 1000 km. Early-time HEMP has a very fast rise time and wide band frequency radiation, which seriously threaten to the electronic information system. The accordant double exponential waveform parameters of HEMP were given by IEC61000-2-9 and MIL-STD-464, as illustrated in figure 1.

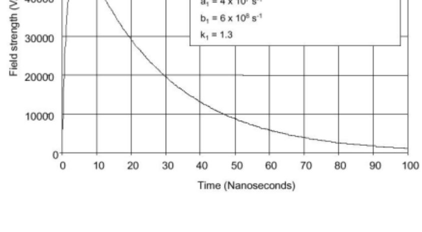

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Figure 1 HEMP wave form given by IEC61000-2-9 and MIL-STD-464

$$E(t) \quad 0 \qquad\qquad t \leqslant 0$$

$$= kE_0[\exp(\quad t) \quad \exp(\quad t)] \quad t>0 \qquad (1)$$

Where $E_0 \quad 50kV \quad m^{\ 1}, k \quad 1.3$

$4.0 \quad 10^7 s^{\ 1}, \qquad 6.0 \quad 10^8 s^{\ 1}$

B. Ultra-wideband and narrow-band high power microwave

Ultra-wideband and narrow-band high power microwave EMP could be produced by non- nuclear explosion or by electricity power transformation, and transported by airplane, missile, ship, or vehicle as flat. The notable characteristic of ultra-wideband EMP is shorter rise time which reaches sub-nanoseconds even to picoseconds level, and spectral content from tens of MHz to several GHz, may disturb wide rang of electrical equipments. The main characteristic of narrow-band high power microwave is that it focus energy within a very narrow spectrum rang, so it may extremely effective while implementing an appointed frequency disturbance. If the power is strong enough, it may result in equipment's physical destroyed.

Gauss pulse and differential gauss pulse and modulated gauss pulse are generally introduced to express ultra-wideband and narrow-band high power microwave form, as illustrated in figure 2 to figure 8.

(1) Gauss pulse

$$E(t) \quad E_0 \exp(\ 0.5(t \quad t_0)^2 / \ ^2) \qquad (2)$$

Where: $E_0 \quad 50kV \quad m^{\ 1}, t_0 \quad 15ns, \qquad 4ns$

Frequency domain expression：

$$E_i(f) \quad E_0 \frac{}{2} \exp \quad \frac{f^2 \ ^2}{4} \quad \exp \quad j2 \quad ft_0 \qquad (3)$$

Waveform in time domain is illustrated in figure 2.

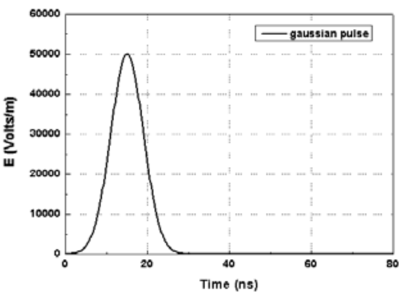


Figure 2 Waveform of gauss pulse in time domain

(2) Differential gauss pulse

Differential gauss pulse is expressed as formula (4). Its waveform in time domain is illustrated in figure 3.

$$E \quad E_0 \frac{t \quad t_0}{t_0} \exp(\ (t \quad t_0)^2 / \ ^2) \qquad (4)$$

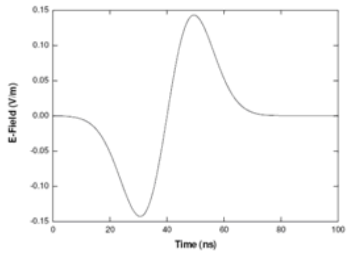


Figure 3 Waveform differential gauss pulse in time domain

(3) Modulated gauss pulse

Modulated gauss pulse is expressed in time domain as formula (5).

$$E_i(t) \quad \cos(\ t) \exp \quad \frac{4 \ (t \quad t_0)^2}{^2} \qquad (5)$$

The fist term of formula (5) is basic wave expression, center frequency is $f_0 \quad /2$. The second term is gauss function expression, t_0 is the center position of gauss function, is a constant, which determines the width of gauss function. Modulated gauss pulse is expressed in frequency domain as formula (6).

$$E_i(f) \quad \frac{}{4} \exp \quad \frac{(f \quad f_0)^2 \ ^2}{4} \quad \exp \quad j2 \ (f \quad f_0)t_0$$
$$\frac{}{4} \exp \quad \frac{(f \quad f_0)^2 \ ^2}{4} \quad \exp \quad j2 \ (f \quad f_0)t_0 \qquad (6)$$

From formula (6) it is realized that comparing modulated gauss pulse with gauss pulse, the spectrum has moved to double sides of zero frequency for f0.

(4) Wideband modulated gauss pulse

In formula (6), if we give f0=1.65GHz, τ =1.48 ns and t0=1.3ns, the spectrum width of pulse is 2.7GHz. Wave form in time domain and frequency domain are illustrated in figure 4 and figure 5 separately.

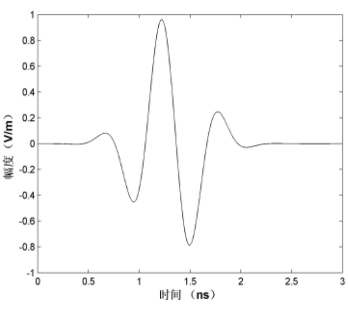


Figure 4 Waveform of wideband modulated gauss pulse in time domain

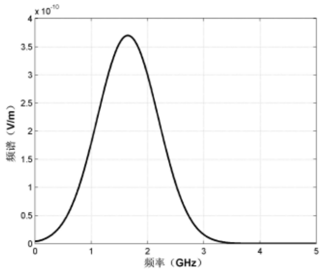


Figure 5 Waveform of wideband modulated gauss pulse in frequency domain

(5) Narrowband modulated gauss pulse

In formula (6), if we give f0=1.28GHz, τ=60 ns and t0=52ns, wave form in time domain and frequency domain are illustrated in figure 6 and figure 7 separately.

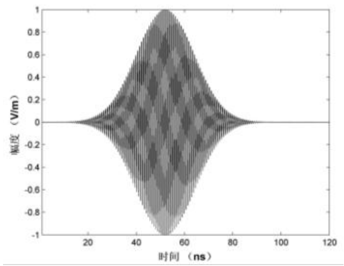


Figure 6 Waveform of narrowband modulated gauss pulse in time domain

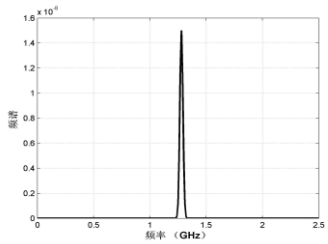


Figure 7 Waveform of narrowband modulated gauss pulse in frequency domain

(6) Using gauss pulse to fit a practical ultra-wideband wave form

A wave from produced by a practical ultra-wideband generator is shown in figure 8. Using gauss pulse to fit the wave form, we get the ultra-wideband pulse expression as formula (7).

$$E(t) = \sum_{i=1}^{3} \frac{a_i}{b_i\sqrt{\pi/2}} e^{-2\left[(t-t_i)/w_i\right]^2} \qquad (7)$$

where : $t_1 = 0.07667ns$, $a_1 = 1.55571$, $b_1 = 0.05207$, $t_2 = 0.24527ns$, $a_2 = 0.44016$, $b_2 = 0.05689$, $t_3 = 0.11903ns$, $a_3 = 5.07040$, $b_3 = 0.08847$, $w_1 = 0.0521ns$, $w_2 = 0.0569ns$ and $w_3 = 0.0885ns$ 。The upper limit frequency of this pulse is up to 15GHz.

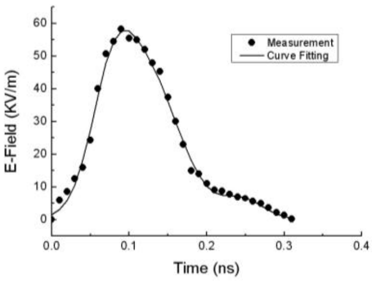


Figure 8 One type of practical ultra-wideband EMP waveform

III. EMP THREATEN TO SENSITIVE ELECTRONIC INFORMATION SYSTEM

A. *EMP threaten to semiconductor element*

While electronic information systems were attacked by EMP in different intension, disturbance, degrade, breakdown, circuits confusion, out of control even to element destroyed would occur in the system. Highly integrative semiconductors and chips are the most destructible elements. The field effect transistor and low noise radio amplifier which structured by field effect transistor, locating at the former end of the RF receive channel, as core parts to amplify the received low level RF and microwave signal, are the most destructible devices too.

According to the destruct mechanism and degree, there are two types of destruction while electromagnetic attacks to the semiconductors, electrical breakdown and thermal breakdown. Electrical breakdown is that EMP disturbs semiconductors from normal work due to its strong electrical field, makes the output signal rough-and-tumble even no output signal. Thermal breakdown occurs while the high power electromagnetic pulse creates strong current inside the element, then produces large quantity of heat to increase the temperature of the element, to melt and break the metal conductor inside of the element, to make semiconductor material melt or break due to the thermal stress, and result in permanent destruction at the lays of material and structure. Because the thermal conductivity of GaAs is smaller than of Si (as shown in figure 9), the thermal effect of GsAs field effect transistor is more remarkable then the traditional Si element, and has more possibility of thermal destruction. The curves of top temperature inside of elements changing with time affected by one single gauss pulse and several pulses are illustrated in figure 10 and figure 11 separately. From the figures we can see that high repeated frequency EMP is more effective to increase the temperature inside of the element to be destroyed. Ordinarily, the destruct threshold of semiconductor is about 10-5～10-2J/cm2，moreover for some more destructible elements, the level is about 0.1～1μJ/cm2. If elements were not to be destroyed, the threshold for instantaneous disturbance or breakdown will decrease

2~3 grades. Table 1 shows the destruction power and energy for different semiconductors.

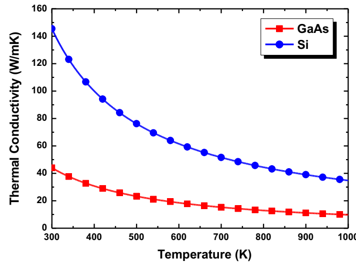


Figure 9 Thermal conductivity of GaAs and Si changes with temperature

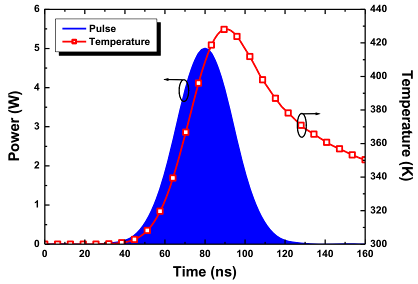


Figure 10 Temperature inside of element changes with time under the stimulation of one single gauss pulse

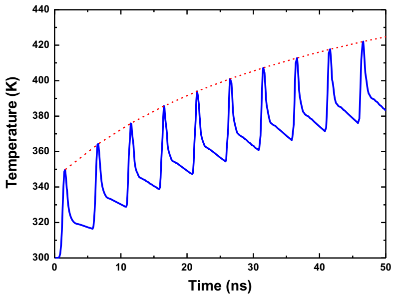
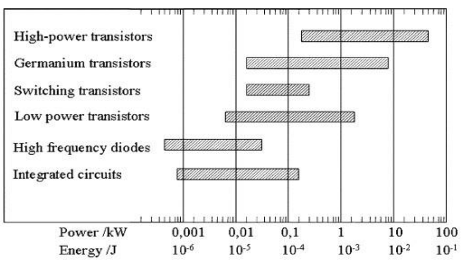


Figure 11 Temperature inside of element changes with time under the stimulation of a serial of gauss pulses

Table 1 Destruction power and energy for different semiconductors.



B. EMP coupling from antennas

The main paths through which EMP enters sensitive electronic information system include ‘front door’ and ‘back door’. For shipboard electronic information system, the front door includes different types of antennas located on the decks and mast for communication, radar, reconnaissance etc. The back door consists of doors and windows of cabin, apertures and slots of case, link cables of equipments etc.

Different types of outside antennas on shipboard ineluctably induce EMP radiation around them and produce strong EMP signal at ports of antennas. Simulation and test indicates that the induced peak voltage at shipboard communication antenna port by ultra-wideband EMP is up to several kV. When the center frequency of modulated gauss pulse is near to the antenna’s resonance frequency, the induced peak voltage at antenna’s output port will be up to tens of kV. As illustrated in figure 12 and figure 13. If pulse voltage with several kV even tens of kV of magnitude entered into the receiver’s RF former modules, it will lead the destructible elements such as RF switch and low noise amplifier and mixer destroyed, even the low level protection circuit, results in the equipments to failure to function.

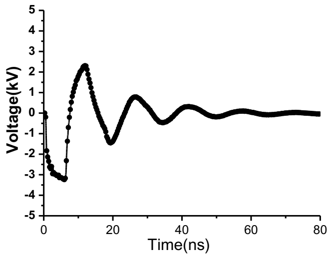


Figure 12 Ultra-wideband EMP induced pulse single on shipboard VHF antenna

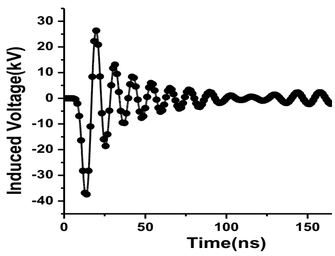


Figure 13 Modulated gauss pulse induced single on shipboard VHF antenna

C. EMP coupling from aperture and cable

EMP radiation may induce big current on the shielding layer of cable. If shielding layer was not grounding well, the strong pulse single will be induced on the core of cable, and transmit into inside of the equipment through cables to disturb the equipment’s work. Figure 14 and figure 15 shows separately the induced current on shielding layer and core of a coaxial-cable which in 5m long, 10cm high to ground, connecting matching loads at two ends, irradiated by gauss pulse field. The irradiation peak field is 1kV/m, and the incidence angle is 45° .

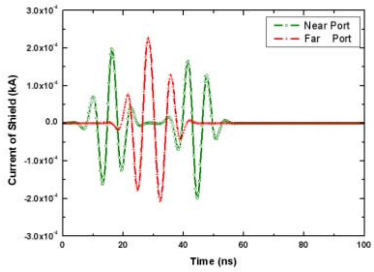


Figure 14 Modulated gauss pulse induced current on the shielding layer of the cable

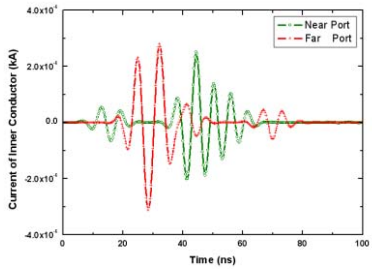


Figure 15 Modulated gauss pulse induced current on the core of the cable

Outside EMP radiation can penetrate into the inside of sensitive electronic information system through apertures or slots of cabin inducting disturbance on the inside cables and circuits to disturb equipment's work. Figure 16 shows the induced disturbance on a 80cm long twisted-pair inside of a case with a 30cm×10cm slot. The two ends of the twisted-pair connect with 50Ω impedance. The irradiating source is ultra-wideband EMP.

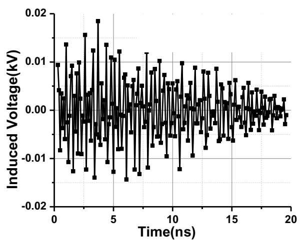


Figure 16 Ultra-wideband EMP induced disturbance on the twisted-pair inside of case

As the digital circuit modules work at relative low level, the induced EMP disturbance on the inside cable will make the system signal overturn, transient upset. For example, the operating frequency and work state change unexpectedly, the control panel becomes out of control, the display works abnormally. Need to turn power off and restart to resume normal operation. This type of disturbance is absolutely unacceptable for those electronic information equipments performing critical, time-urgent missions. If the shielding effectiveness of cabin and case was too weak, the strong EMP disturbance induced on the inside circuit will cause the computer system and input/output module permanent damage.

IV. EMP PROTECTION FOR ELECTRONIC INFORMATION SYSTEM

According to EMP coupling characteristic of electronic information system, the EMP protection measures mainly include screen, filter, and voltage-limit. To implement the effective EMP protection for electronic information system, it is necessary to perform reasonable protection measure to all coupling paths separately based on the system operating frequency, operating signal level, location and flat structure characteristics.

A. screen

Screen is one of the most effective measures to prevent and reduce EMP threat. There are different screen requirements for different types of EMP. Because lightning and HEMP both have high electrical field and magnetic field components, it is required that the screen material should provide good shielding effectiveness for both electrical field and magnetic field, and this will greatly increase the difficulty of screen. Steel plate can provide better magnetic screen effectiveness than aluminum plate. For high power microwave and ultra-wideband EMP, it only requires that the screen material has good electrical shielding effectiveness due to the small magnetic component. On the other hand, the higher the frequency is, the stricter for the aperture deal with will be. If the aperture was great than 1/100 wave length, it will lead relative high energy leak.

The key of the screen for shipboard electronic information system is to deal with the apertures of cabin, observe windows, vent, the apertures of equipment case, shielding layer of cable, etc. Ordinary weather door and observe window and vent cannot provide sufficient shielding effectiveness, so special material and arts and crafts should be introduced to increase the full system shielding effectiveness. There are many measures to increase the shielding effectiveness, such as using high performance electric screen glass in observe windows, covering with metal meshwork on vent or using waveguide-blow-cutoff piping vent, continuous circumferential weld or press connection or flexible connection, well disposing the run through conductors of shielding room at the entrance and so on.

B. Filter

Commonly，EMP contains quite wide spectrum. For electronic information equipments which operating at special frequency or a certainty rang of frequency band, filter can restrain effectively EMP energy from coupling and transmitting inside. Band-pass filter can be used at RF path of communication and radar equipments which operating at RF or microwave band. Low-pass filter can be used on the power lines and control lines on which transmitting low frequency signals. Band-pass and low-pass filters prevent the great mass of out-of-through-band EMP energy from going into inside of electrical equipments.

The frequency selection surface (FSS) used for the purpose to decrease the antenna's radar cross section is capable to provide EMP protection function too. FSS permits only special frequency electromagnetic wave to penetrate through it, but strongly reflect the other frequencies. FSS acts as a space filter can be used at antenna cover to restrain wide-band EMP radiation in space from going into antenna and RF path of sensitive equipments.

C. *Voltage-limiting*

Large number of voltage-limiting circuits and modules are employed in EMP protection design. Screen measure is not suitable for outside antennas. EMP signals inside of the operation frequency band are not possible to be restrained by filter measure. Voltage-limiting should be used at these conditions. When the system attacked by EMP, the protection circuits or modules will be short and lead the EMP energy to ground to protect the sensitive elements. After the EMP impulsion, the protection modules or circuits return to normal open state. Designing the protection circuits with a appropriate threshold level and current capacity, the operation signal could be ensured to pass through with acceptable inset loss, as well as the strong EMP signal will be prevented effectively from destroying the sensitive circuits.

The key of protection circuits and modules are response time and current capacity. The ordinary lightning protection modules with μs level response time hardly work to the NEMP and ultra-wide band EMP with ns and ps level rise time. Therefore, it is required to select quick-response protection device for electronic information system. In the design of circuit and construction, it is very important to reduce lead or trace inductance as possible to ensure the quick response.

D. *Else protection measures*

A good arrangement is important for EMP protection. Due to the strong magnetic field component of Lightning and NEMP, reducing the magnetic inductance loop area in the system arrangement will effectively decrease the threat of EMP. The relative measures include reducing the height of cables to ground as possible, arranging the cable close to the cabin wall or deck, reducing the length of cable as possible, using shielded kinking cables which have good performance to reduce difference model disturbance, disposing the highly sensitive equipments to cabins under the main deck, etc.

It is important to give attention to EMP protection during the circuit design. If the non-sensitive elements are capable to perform the function of the circuit, never use the sensitive elements while selecting elements for the circuit. For example, the vacuum tube has better EMP enduring performance than transistor. For the circuits which may be destroyed by EMP, the protection circuits must be put in front of them to stop EMP from reaching the destructible module. For especially important equipments, multi- protection circuit is needed. Furthermore, well grounding could reduce EMP coupling and ensure the different types of protection measures to work effectively.

V. Acknowledgment

The method of EMP coupling analysis is similar to EMC analysis. EMC technique such as screen, filter, bonding and cable layout can be used in EMP protection design. In these aspects, EMI control and EMP protection have the same principle, but they have different protection grades. Therefore, appropriate protection grade and protection requirements should be chosen according to the EMP threat and the destructible characteristics of system and flat before the electronic information system protection design. It determines the idiographic design of EMP protection.

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