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Summary of Research on Strong Electromagnetic Pulse Effect in Radar Receiver

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Abstract

Strong electromagnetic pulses can be generated by nuclear explosions and high-power microwave weapons. It has the characteristics of short rise time, high energy, high field strength and wide range. Among them, high-altitude nuclear explosion electromagnetic pulse (HEMP) is a kind of instantaneous electromagnetic radiation that is accompanied by high-altitude nuclear explosion (≥30Km).Its frequency coverage is very wide, from very low frequency to hundreds of megahertz, the field strength is very high and there is a very short pulse period, which can pose a serious threat to the electrical and electronic systems on the ground and aircraft in a wide range. With the rapid development of science and technology and the application of large-scale integrated circuits, the study of the electromagnetic pulse coupling effects of high-altitude nuclear explosions has become a hot issue. This article first introduces the various parameter attributes of nuclear electromagnetic pulses, and then analyzes the corresponding hazard pathways and research status for the two different approaches of "front door coupling" and "back door coupling". Finally, the finite time domain difference method (FDTD) is introduced.

Keywords

EMP, Coupling effect, FDTD.

1. Introduction

According to the international standards established by the International Electrotechnical Commission, electromagnetic pulses can be divided into high-altitude nuclear explosion electromagnetic pulses (HEMP) [1], high-power microwaves (HPM) [2], and ultra-wideband electromagnetic pulses (UWB) [3] according to different parameters such as power and pulse width. With the rapid development of science and technology, the electromagnetic environment is becoming more and more complex, and the electromagnetic pulse of high-altitude nuclear explosions is the product of a kind of high-altitude nuclear explosion. The electromagnetic radiation field generated will not only cause interference and damage to electronic circuits and equipment [4-6], but even pose a threat to national defense facilities and national security. Therefore, it is of great significance to study the electromagnetic pulse of high-altitude nuclear explosion and its various electromagnetic coupling effects.

2. High Altitude Explosion Electromagnetic Pulse

Nuclear explosions can generally be divided into ground nuclear explosions, low-altitude nuclear explosions and high-altitude nuclear explosions. Any form of nuclear explosion can generate electromagnetic pulses, but the forms are different. The electromagnetic pulses produced by high-altitude nuclear explosions are more harmful. The nuclear electromagnetic pulses are strong, rich in high-frequency components, and cover a wide area. For high-altitude nuclear explosions above 100km, the high field strength produced by them can cover thousands of kilometers on the ground.

2.1. The production of High Altitude Explosion Electromagnetic Pulse

The high-energy instantaneous gamma rays (The average energy is about 1.5~2MeV) produced by the nuclear explosion ionize air molecules in the form of Compton scattering. Compton electrons that are scattered out of high-speed flight form a flow of Compton electrons that are basically radial. At the same time, the high-speed Compton electrons ionize air molecules to produce a large number of secondary electrons during the movement. The core of the air has a certain conductivity, the core of the explosion forms a positive charge accumulation, and the negative charge accumulation is formed away from the core of the explosion, and an electric field is established, which will prevent the Compton electrons from spreading out. Due to the action of the electric field, a back current that is in opposition to the Compton current, that is, the ohmic current, finally reaches a certain stable value, that is, the saturated field. There is a distributed charge near the saturation field, and its inhomogeneity forms a surface current. These currents can be spread out by a series of natural frequency modes of sphere oscillations. Due to the existence of the ground, the change of atmospheric density with height, and other asymmetry factors, the Compton current and the ohmic current are not spherically symmetrical. They excite electromagnetic pulses that radiate outward in the course of time changes. X-rays, high-energy neutrons and other radioactive elements released during a nuclear explosion can also excite electromagnetic pulses when they collide with the air.

2.2. The Time-frequency Characteristics of High Altitude Explosion Electromagnetic Pulse

When a nuclear weapon explodes at high altitude, a pulse period generated by it can be divided into early, mid and late [7]. Among them, the early electromagnetic pulse radiation field has a large peak electric field (tens of kilovolts per meter), a fast leading edge (on the order of nanoseconds), a short duration (about 100ns), and a wave impedance of 377Ω, which has a major destructive effect on integrated circuits. The mid-term signal amplitude is 10～100V/m, the appearance time is about 100ns, and the duration is tens of milliseconds. Late HEMP is characterized by low electric field amplitude (tens of millivolts per meter), slow front edge (on the order of seconds), and long pulse duration (hundreds of seconds). When considering the total energy of HEMP, the middle and late stages of HEMP are negligible compared to the early stages. Therefore, the harm of early stage HEMP to the circuit system is generally studied.

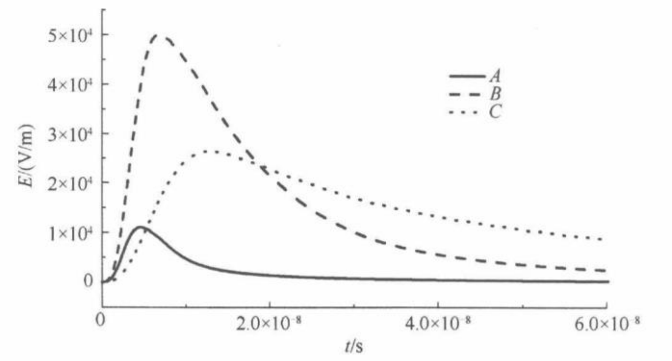

Figure 1: The time domain diagram of HEMP

Different burst heights and different equivalents produce different time-domain waveforms of HEMP at different locations on the earth's surface. The more common waveform standard, the waveform function constructed by the spectrum envelope method is:

$$E_{1(t)} = \begin{cases} 0, & t \le 0 \\ E_{01} k_1 (e^{-a_1 t} - e^{-b_1 t}), & t > 0 \end{cases} \tag{1}$$

In the formula, the unit of E_1 is V/m; the unit of t is s; $E_{01} = 5 \times 10^4$ V/m; $a_1 = 4 \times 10^7 s^{-1}$; $b_1 = 6 \times 10^8 s^{-1}$; $k_1 = 1.3$. Through the analysis of the electromagnetic field spectrum, it is found that in the 0~1GHz frequency band, 90% of the frequency spectrum is concentrated in the 0~100MHz frequency band, of which the 10kHz~10MHz spectrum has the highest amplitude.

3. Research Status of Hemp Coupling Effect

Similar to other strong electromagnetic pulses, HEMP energy coupling can be divided into front door coupling and back door coupling. Front-door coupling means that nuclear electromagnetic pulses are linearly coupled into the receiving and transmitting system through media such as antennas and transmission lines on the target to destroy the front-end electronic equipment, including power cords, telephone lines and shielded signal cables, buried cables and ground loops; Backdoor coupling refers to coupling into the system through the gap or hole on the target, disturbing its electronic equipment, making it unable to work normally or burning the microelectronic devices and circuits in the electronic equipment [8-10]. At present, the domestic coupling effects on HEMP are mainly concentrated on the research of antennas, cables and apertures.

3.1. Backdoor coupling

For electronic equipment, the most direct and effective way to reduce the interference of HEMP to the system is to take shielding measures [11]. Using the shielding effect of the metal cavity, the system is placed inside the cavity, which can effectively resist the influence of external electromagnetic radiation. On the other hand, the power interface, the circuit connection between the system circuit, etc. will inevitably increase the hole in the shielding shell. Strong electromagnetic pulses usually carry huge amounts of energy. If the incident electromagnetic energy is strong enough, the air in the gaps and seams of the case can be ionized to become a good conductor, which destroys the shielding effect of the case structure and causes the electromagnetic pulse energy to penetrate into the device case. Therefore, the analysis of the shielding effectiveness of the system is the focus of the study of HEMP backdoor coupling. Liu Shunkun used the finite difference method to study the coupling of ultra-wideband, fast-rising electromagnetic pulses and nuclear electromagnetic pulses to the apertures of the target cavity. It is found that compared with NEMP, FREMP and UWB are easier to couple into the cavity, and it is easier to produce cavity resonance [12]; Yu Guoyin et al. studied the rectangular hole coupling of nuclear electromagnetic pulses and found that the electromagnetic field in the screen mainly exists near the hole [13]. The size of the small hole is reduced, and the field strength in the cavity is also reduced. When the width of the small hole is reduced to half of the original, the relative value of the field strength in the cavity is reduced from 87% to 57%; Fu Jiwei analyzed the coupling effects of electromagnetic pulses with different polarization modes on square, rectangular and porous holes under the same aperture area. It is found that when the pulse polarization direction is parallel to the short side of the rectangle, the coupling energy is the largest [14]; In view of the characteristics of the double-layer shielded cavity with openings, Wang Dianhai found that changing the distance between the two holes will also affect the shielding effectiveness and resonance frequency of the double-layered cavity. The larger the hole spacing, the better the shielding effectiveness and the higher the resonance frequency. Compared with a single-layer cavity, a double-layer cavity will significantly improve the shielding effectiveness and resonance frequency [15]; Lin Xia uses simulation software to analyze and find that the shielding and protection capabilities of electronic enclosures of different materials are also different. The shielding effectiveness of the chassis can be improved by mounting absorbing materials, adding conductive rubber to the slits, etc. [16]; Sun Fengjie used the method of field-circuit combination to study the signal integrity problem caused by strong electromagnetic pulse interference on the RS232 serial port in the electronic chassis. It is found that the pin of the load chip can sense the peak voltage, which may break down the internal transistor and protection circuit of the chip, and also cause internal logic errors [17].

3.2. Front door coupling

There are usually two coupling paths for HEMP, namely conduction and radiation. The premise of conductive coupling is that there must be a circuit connection channel between the interference source and the coupling device. Radiation coupling is to transfer the energy carried by electromagnetic pulses through electromagnetic radiation. The antennas, holes in the structural shells of electronic devices, and transmission lines can all be radiated coupling. The coupling of HEMP into the system through the antenna is a typical and main front-door coupling method. The coupling strength can be calculated through the antenna design characteristics, and it is the highest when the electromagnetic wave frequency is equal to the antenna design frequency. Antennas, as an important device for electronic systems to exchange information with the outside world, have been widely used in various electronic devices. It is the same as the human ear, nose, mouth and tongue and other organs. While perceiving external information, it is also easily disturbed by external information. The spike voltage of HEMP coupled into the system through the antenna may directly destroy the internal electronic circuit. There is a radio frequency front end for processing high frequency signals between the antenna and the signal processing circuit. Many researches have been carried out on the antenna and radio frequency front end in the HEMP environment. Tan Zhiliang and others elaborated on the research content of RF front-end strong electromagnetic pulse protection, and summarized and analyzed the current electromagnetic pulse protection research work carried out at home and abroad from the perspectives of theoretical analysis, modeling simulation and experimental evaluation; Han Pengwei and others adopted the integrated design of transient limiting and steady-state filtering, studied and designed the RF front-end protection module and limiter, and optimized their performance [18]. Wu Gang and others evaluated the threat of HEMP to a certain type of shortwave receiving antenna system, and analyzed that its energy is mainly concentrated in the range of 1-100MHz, and has strong in-band coupling to shortwave (3-30MHz) and ultrashortwave (30-300MHz) antennas[19]. From the point of view of electromagnetic field, Wu Yujiang et al. introduced the concept of "reaction" and passed the reciprocity theorem, and strictly proved that the receiving antenna can be equivalent to an open circuit voltage model, and pointed out that the equivalent circuit parameters of the receiving antenna are not unique [20]; Zhen Kelong conducted ADS simulation analysis on the interference influence of strong electromagnetic pulses on radar receivers, and proposed corresponding protection measures against electromagnetic pulses [21]; Zhang Tiancheng gave a numerical analysis method of the transmission line equation combined with the semiconductor physical model in view of the impact of the energy generated by the coupling of the nuclear explosive electromagnetic pulse through the antenna into the RF front-end on the device performance [22]; Zheng Fuquan simulated the shell fuze in HEMP environment with or without shell protection, and the results showed that the attenuation of the fuze shell to the electric field was 27.9dB. And under the protection of the shell, it can work normally when the electric field intensity is less than 45kV/m. Without protection, when the peak of the strong electromagnetic pulse electric field intensity reaches 15kV/m, the chip will restart and reset, causing the fuze to detonate and fail; When the field strength reaches 50kV/m, the chip may be permanently damaged [23].

3.3. Numeral Calculations

On the basis of Maxwell's equations, the research of electromagnetic theory focuses on obtaining analytical solutions to electromagnetic field problems. However, the electromagnetic field problems to be solved in the application of cutting-edge science and technology are often complex, and it is not possible or difficult to obtain analytical solutions. Until the 1960s, the emergence of electronic computers ushered in a new era of computational electromagnetic field research. Several types of electromagnetic field numerical calculation methods represented by finite difference method, finite element method and method of moments have appeared one after another, and computational electromagnetics has ushered in a period of vigorous development [24-26]. In 1996, K.S. Yee first proposed a new method of electromagnetic field numerical calculation-finite difference time domain method (FDTD). After two decades of development, the FDTD method has gradually matured. Since the late 1980s, the FDTD method has entered a new stage of development, from maturity to a stage that is widely accepted and applied. The FDTD method is one of the effective methods to solve complex problems. It is a numerical algorithm directly based on the differential equation of the electromagnetic field in the time domain. It directly approximates the Maxwel curl equation with the second-order precision central difference in the time domain, thereby converting the solution of the time domain differential equation to the iterative solution of the difference equation. It is a computer simulation of electromagnetic field and electromagnetic wave motion law and motion process. In principle, it can solve technical and engineering problems of electromagnetic field and electromagnetic wave in any form. And it has lower requirements for computer memory capacity and faster calculation speed, which is especially suitable for parallel algorithms. Now the FDTD method has been widely used in antenna analysis and design, target electromagnetic scattering, electromagnetic compatibility, microwave circuit and optical path time domain analysis, biological electromagnetic dosimetry, transient electromagnetic field research and other fields [27].

4. Conclusion

With the continuous update and development of science and technology, the future electronic system will have more in-depth research on HEMP, with the following characteristics:

(1) The research objects will be deeper and more systematic. At present, the research objects are mainly focused on simple targets at the device level and lack systemicity. For large and complex systems, electromagnetic pulse coupling methods are becoming more and more complex. Therefore, accurate modeling and rapid analysis of the system-level electromagnetic pulse energy coupling law has become a key issue to be solved in the study of EMP effects [28].

(2) The simulation program is modularized. Although the electromagnetic radiation problem is becoming more and more complex, some modeling and simulation programs are becoming more and more modular. For example, the parameter setting of the simulation material, the setting of boundary conditions, etc., are more convenient to use in computer language, and it is possible to deal with complex problems.

(3) The numerical algorithm of electromagnetic field is more complete. Based on the original numerical calculation methods such as finite difference time domain, finite element, method of moments, etc., the development direction of each algorithm is to improve calculation accuracy, increase the ability to simulate complex structures, reduce computer memory and calculation time, and expand its application range.

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