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Non-nuclear Electromagnetic Pulse Threat of Critical Infrastructures and Protection Strategies

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Abstract: Major infrastructure is vital for the modernization and operation of a country, and its safety is crucial for national security. In recent years, the technology for generating non-nuclear electromagnetic pulse (EMP) sources has gradually matured and developed to be universal and concealed. Non-nuclear EMP has become a realistic threat to major infrastructure. Therefore, ensuring the electromagnetic safety of major infrastructures is an urgent strategic task for China. This study considers the non-nuclear EMP threat of major infrastructure as the research object, clarifies the basic concepts and significance of EMP protection for major infrastructure, and analyzes the measures adopted in this field by developed countries from the perspectives of national policies, industrial standards, fundamental research, and emergency management. Additionally, this study summarizes the key technologies for efficient non-nuclear EMP protection, focusing on forward design, equivalent tests and evaluations, and threat monitoring and prediction. Moreover, this study analyzes the current status and existing challenges of the non-nuclear EMP protection of major infrastructure in China. Several fundamental strategies are proposed, including strengthening government leadership, promoting scientific research, formulating standards and guidance, stimulating the vitality of enterprises, conducting classified and staged implementations, boosting talent cultivation, and promoting public training. This study can provide a fundamental reference for the non-nuclear EMP protection of major infrastructure and further support China in managing new threats.
Keywords: critical infrastructure; electromagnetic pulse; graded protection; emergency response; electromagnetic protection

1 Introduction

Major infrastructure is closely related to the modernization and operation of a country. If damaged, it will significantly impact social, economic, and national defense security. Therefore, infrastructure security has become one of the core elements of national security [1–4]. The informatization and networking level of major infrastructure is constantly improving, and the overall architecture of major infrastructure is changing significantly. For instance, low-voltage subsystems, including sensing, communication, control, and data storage, play an increasingly critical role in the operation and management of major infrastructure. The disturbance or damage of low-voltage subsystems will directly endanger infrastructure and national security. Therefore, high-power electromagnetic pulses (EMPs) pose a potential threat to low-voltage subsystems, and it has become common

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understanding that high-power EMPs may endanger the security of major infrastructures. High-power EMPs can be mainly categorized into nuclear and non-nuclear EMPs. Both types threaten major infrastructure, such as electric power grids, high-speed railways, and wireless communication systems. In recent years, generation technologies for non-nuclear EMP have been developing rapidly and practically, becoming a potential threat to major infrastructure security.

Major infrastructure has multilevel connectivity, which satisfies the basic characteristics of a complex network. Early research mainly focused on the network structure and key parameters. Power grids with voltage levels of 110 kV or higher in China have a large clustering coefficient and small average path length and belong to the small-world complex network [5]. However, high-speed railways in China have several hub nodes that play a key role in the security of the railway network, and is a scale-free complex network [6,7]. Therefore, major infrastructure networks are usually reflected in small-world, scale-free network characteristics, which may have good resistance to random or non-critical node failures. However, when facing many intentional interferences or key node failures, cascading failure can easily occur and lead to the large-scale failure of major infrastructure [8–10]. Scholars in China have conducted systematic investigations on the complex network architecture of major infrastructure and have provided specific suggestions for developing resilient power grids [4,11]. Additionally, numerical simulations of high-power EMP effects, protection of local nodes, and experimental tests on the local nodes of major infrastructure were also performed [12–16], which provides a solid foundation for the implementation of high-power EMP protection.

This study focuses on the non-nuclear EMP threat to major infrastructure in China, summarizes the experiences and lessons learned regarding the high-power EMP protection of major infrastructure in developed countries, and analyzes the weaknesses and bottlenecks of China in this field. It is beneficial to use the advantages of the late mover to address major security risks efficiently. This study strives to discuss the significance of this topic, the development status, major challenges, and key technologies of high-power EMP protection from the perspective of system engineering, and then propose a basic strategy for the EMP protection of major infrastructure in China.

2 Concepts and demands of non-nuclear EMP protection in major infrastructure

2.1 Concepts of non-nuclear EMP protection in major infrastructure

Major infrastructure refers to a large-scale facility network related to the national economy and livelihood of people, social operations, and national security, and mainly involves core areas such as electricity, transportation, communication, and finance. These major infrastructures support each other and form a closely intertwined complex network. The failure of certain nodes within the infrastructure network is prone to produce a chain reaction, and restoring the function of major infrastructure in a short time is difficult. Most developed countries have attached considerable importance to the security issues of major infrastructure, and some countries have established special agencies to manage them.

High-power EMP refers to the transient, high-power density of electromagnetic fields and waves, with high instantaneous power (peak power to GW), high peak field strength (tens of thousands of V/m), changeable waveforms (such as narrow band, wideband, ultra-wideband, with carrier, carrier-free, and others), and a wide frequency range (several MHz to tens of GHz, Fig. 1). High-power microwave (HPM) and EMP generators have developed rapidly, and the EMP delivery platforms have been extended to aircraft, missiles, vehicles, and portable platforms. Moreover, some simple devices can produce high-power EMPs, which pose a threat to major infrastructure.

Consider the high-speed railway network as an example to illustrate the potential threat to major infrastructure (Fig. 2). The high-speed train control system (TCS) is mainly composed of on-board and ground equipment, which realize two-way data communication through the specific mobile communication system of the railway. To provide a control signal transmission channel to the train, the high-speed TCS provides wireless or electrical interfaces between the equipment [17,18]. These interfaces are important coupling routines for high-power EMP in the TCS. The TCS then may be damaged by the EMP, causing failure and affecting the normal operation of the railway network. China will coordinate the development of a high-speed maglev system of 600 km/h and high-speed railway of 400 km/h, according to the *Outline for Building a Strong Transportation Sector in China* (2019). After the train operation speed is further improved, the anti-interference ability of the TCS, particularly the anti-EMP ability, is required.

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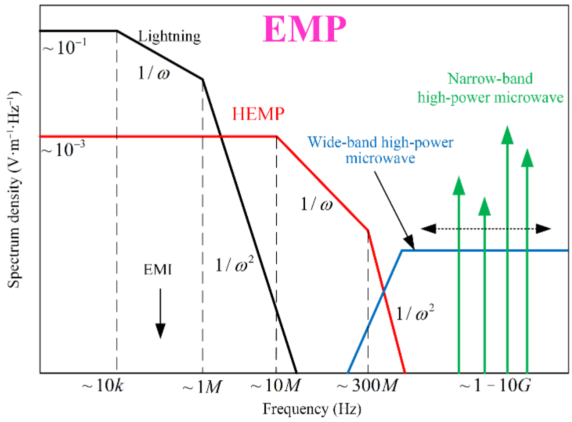

Fig. 1. Typical spectrum of different EMPs.

Note: HEMP refers to high-altitude nuclear EMP; EMI refers to electromagnetic interference;

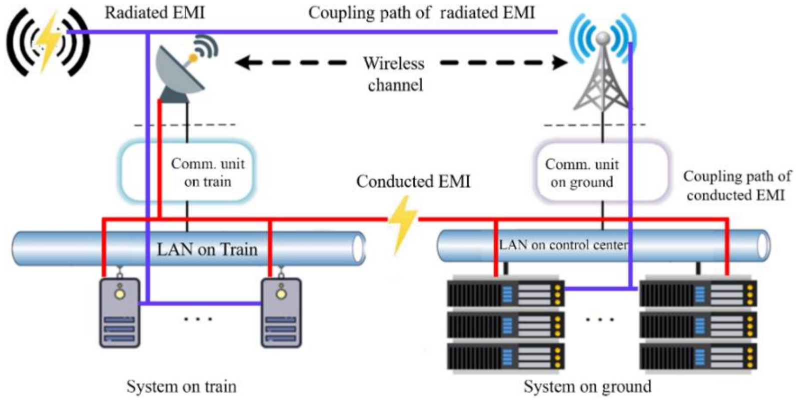

Fig. 2. EMI coupling paths in a typical high-speed railway control system.

Note: LAN refers to local area network

2.2 Demand for non-nuclear EMP protection in major infrastructure

2.2.1 Ensuring national security in the electromagnetic domain

China increasingly attaches great importance to national security in the electromagnetic domain, listing it as a core element of national security. Security in the electromagnetic domain is included in the *National Defense Law of the People's Republic of China*. The protection of major infrastructure has been gradually standardized, and the *Regulations on the Security and Protection of Key Information Infrastructure* included information infrastructure in the scope of key protection. The *14th Five-Year Plan for National Emergency System* proposes the construction of emergency communication and emergency management information systems as key projects to comprehensively improve the emergency communication resource dispatching and comprehensive application capabilities of China.

Currently, the protection measures taken regarding the major infrastructure security in China focus on hardware and information network security; however, electromagnetic security has not been clearly planned. Threats to major infrastructure in the electromagnetic domain are invisible and untouchable. They are abstract in concept, easy to be ignored by all parties, and may be maliciously exploited by other parties. There are no obvious signs of malicious strong electromagnetic pulse attacks, and the established electromagnetic spectrum monitoring sites lack effective means of electromagnetic pulse monitoring, which may not be able to effectively collect evidences of various strong electromagnetic pulse events. Due to the lack of effective design and verification of non-nuclear strong electromagnetic pulse protection, all kinds of major infrastructures are vulnerable, which may lead this country into a disadvantageous situation in special circumstances. Therefore, it is necessary to systematically plan and actively implement strong electromagnetic pulse protection measures for major infrastructures, thus to reverse the adverse situation and ensure the operation safety of major infrastructures.

2.2.2 Addressing the threats of non-nuclear EMP

The threat of a high-altitude nuclear EMP (HEMP) to major infrastructure is well known. A series of high-altitude nuclear weapons tests in the 1960s produced high-power EMPs that affected power transmission lines over thousands of kilometers, causing widespread damage to communication, broadcasting, transportation, and other systems. After the *Treaty on the Non-Proliferation of Nuclear Weapons* came into effect, developed countries gradually shifted to generating non-nuclear EMP technologies.

Using microwave technology can produce high-power EMPs in the vicinity of major infrastructure, disturb various low-voltage equipment within a certain distance, and even physically burn important electronic equipment. HPM technology and its armament has developed rapidly, including new-generation methods and compound effects on electronics [19–22]. HPM technologies continue to be developed, with the maximum carrier frequency reaching tens of GHz. Conventional vacuum, relativistic, and solid-state electronic devices (Fig. 3) can generate HPMs. The peak output power of relativistic devices is very high (tens of GW). Conventional vacuum devices are flexible in terms of bandwidth and power level, and multiple devices can achieve a peak power of 100 MW or higher through spatial power synthesis. Simple and inexpensive non-nuclear EMP-generation devices have emerged, which are flexible in potential applications. Non-nuclear EMP attacks are difficult to prevent and control in advance, and the induced major infrastructure losses are difficult to recover quickly. Therefore, non-nuclear EMP has become a realistic threat to major infrastructure.

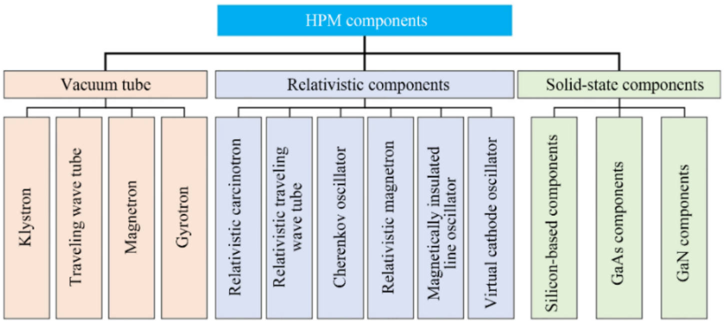

Fig. 3. Typical types of HPM components.

2.2.3 Enhancing public awareness of electromagnetic security

The successful experience of earthquakes, fires, and other disaster prevention shows that publicity and the exercise of relevant self-rescue knowledge can effectively prevent secondary injuries and losses caused by public panic. Therefore, the School of Electronics and Information Engineering of Beihang University conducted a social questionnaire survey (2021) to investigate the public understanding of related fields and promote the social popularization of electromagnetic security-related knowledge. A total of 1060 valid samples were obtained from the questionnaire survey, covering universities, enterprises, scientific research institutes, and other sources. Overall, respondents had a high level of education. However, only approximately one-third of the respondents knew that the July 23 Ningbo–Wenzhou Line accident originated from lightning strike effects, and less than one-fifth of the respondents knew that the US–Canada power outage (2003) originated from transformer failure caused by geomagnetic disturbances (GMD). The public awareness level of high-power EMPs and their threat to major infrastructure is generally lacking.

It is worth mentioning that the survey found that the respondents had a low tolerance for major infrastructure faults caused by EMP. Approximately 5.5% of respondents reflected acceptance of high-speed railway delays exceeding 3 h; approximately 8.5% of respondents reflected acceptance of power failure exceeding 3 h; and approximately 5.1% of respondents reflected acceptance of communication interruption exceeding 3 h. In contrast, 69.2% of respondents could not accept communication interruption of any duration. The results show that the public knows little about threats in the electromagnetic domain and is intolerant to major infrastructure failures. If a related failure occurs, a general lack of preparation will very likely cause public panic or even social risks.

3 Strategic plan for the EMP protection of major infrastructure in foreign countries

3.1 Releasing national policies

The United States of America (USA) was the first country to launch an EMP protection plan for major infrastructure. The EMP Committee of the US Congress was formally established in 2001, promoting extensive

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theoretical and experimental research. In 2008, the committee issued a series of reports discussing EMP threats and protection recommendations for ten major infrastructure categories. In 2017, the US Congress reorganized the EMP Committee to comprehensively promote its influence on political, economic, military, and other fields. The committee performs systematic research work, which serves as a reference for subsequent scientific research and national strategy formulation.

Under the recommendation of the EMP Committee, the United States Congress passed the *Critical Infrastructure Protection Act* (2015). In 2019, a presidential policy directive emphasized the electromagnetic security of major infrastructure and demanded the strengthening and maintenance of the security, operation, and resilience recovery capabilities of major infrastructure. In this sense, the USA entered the strategic implementation phase of the EMP protection plan. The *Electromagnetic Pulse Resilience Action Plan* (2017) of the U.S. Department of Energy proposes to raise awareness of the threats, effects, and influences of high-power EMP, identify key facilities, and conduct extensive tests of the EMP protection measures. The *Strategy for Protecting and Preparing the Homeland Against Threats of Electromagnetic Pulse and Geomagnetic Disturbances* (2018), published by the U.S. Department of National Security, addresses the need to improve the rapid response and effective recovery of EMP-related events. Additionally, to protect 16 categories of major infrastructure, the U.S. Department of Homeland Security designated a risk management bureau to better implement major infrastructure-related safety efforts.

3.2 Publishing industrial standards

The US industry is still presently in the analysis and wait-and-see stage of the EMP protection of major infrastructure. The power industry is comparatively further advanced, with two sets of industry standards for GMD threats. The TPL-007-1 standard of the North American Power Reliability Company requires the power transmission company to evaluate the weak links in the transmission system and develop corresponding production plans based on a once-in-a-century GMD event. The EOP-101-1 industry standard requires that the power sector optimize operation plans, production processes, and procedures to ensure that the impact of GMD events is reduced. Under the agreement, U.S. power companies can share transformers and other key equipment to improve the recovery capability of the power grid. The Coordination Committee of the Electric Power Department, together with other key infrastructure management departments, jointly formulated the *Transformer Emergency Transport Guidance Act* in which the deployment of large idle transformers can be rapidly implemented using railways, highways, and waterways. Thus far, the non-nuclear EMP protection requirements for major infrastructure have not been included in the relevant industry standards.

Given the popularity and importance of major infrastructure, it is appropriate to implement hierarchical protection and obtain a better efficiency and cost ratio. The EMP protection level of major infrastructure can be divided into four levels according to the allowable failure time of the major infrastructure [23], namely, Level 1, allowing long service interruption; Level 2, allowing service interruption for several hours; Level 3, allowing service interruption for several minutes; and Level 4, allowing service interruption for several seconds. (1) A key point of Level 1 protection is ensuring that personnel on duty have backup power, food, water, and other necessary supplies to operate and maintain the mission-critical systems of major infrastructure. (2) Level 2 protection requires the addition of surge protective devices (EMP filters, discharge tubes, and others) to the power cord, data line, and antenna port. It does not require expensive electromagnetic shielding rooms; therefore, this is a cost-effective method. (3) Level 3 protection usually requires an electromagnetic shielding rack or a shielding room. (4) Level 4 protection is applicable to infrastructure directly connected to life and property safety (such as nuclear power plants, life support systems, air traffic control systems, and high-speed rail control systems). It is recommended that the shielding effectiveness for high-frequency EMP should reach 80 dB within a 10 GHz bandwidth [23].

3.3 Focusing on fundamental research

USA attaches great importance to the catastrophic damage that HEMP and GMD can cause to major infrastructure. The Congressional EMP Committee has studied the EMP risk in ten types of infrastructure, revealing that the risk level for energy and communication infrastructure is the highest [1]. Accordingly, the US Department of Energy launched the Research Project on EMP effects and Protection of Power Grid (2016). This project includes threat analysis, electromagnetic vulnerability (EMV), simulation methods, measurement apparatus, and protection. Because the research on EMP protection of major infrastructure is highly complex and interdisciplinary, the research work was mainly performed at the Oak Ridge, Los Alamos, and Idaho National Laboratories [24]. The Sandia National Laboratory analyzed the statistical effects of HEMP [25] and developed a surge protection diode based on gallium nitride technology with a breakdown voltage of 6 kV [26]. This indicates that the USA is leading the world in the protection against strong EMPs.

Through the Seventh Framework Plan, the European Union funded several key research projects on the EMP protection of major infrastructure, such as the protection of critical infrastructures against high power microwave threats, protection of critical infrastructures against electromagnetic attacks, and security of railway against electromagnetic attacks [27,28]. These studies focused on the threat generated by HPM devices.

3.4 Strengthening emergency management and training

To raise the awareness of the public to the potential security threats to major infrastructure, the GridEx exercise has been held every other year to strengthen the capability of industry to deal with major infrastructure failures and ensure an orderly response to accidents. These exercises not only improve the joint response capacity of power companies and management departments but also help alleviate public panic if major accidents occur. For example, the GridEx VI exercise, held in November 2021, set the goal of "exercise the resilience of the North American electricity system in the face of a coordinated attack from a state-sponsored adversary". More than 450 organizations and 6500 people from the power sector, management departments, and specialized agencies participated in this exercise. This demonstrates that the USA has included organized malicious attacks in the management of major infrastructures.

4 Key Technologies of non-nuclear EMP protection in major infrastructure

EMP protection refers to the technical approaches that eliminate the interference or damage of EMPs to information systems, and constitutes the theoretical basis for guaranteeing the efficiency and vitality of major infrastructure. The EMP protection of major infrastructure needs to solve many problems, such as policy, management, technology, and economy. China's technical research in this field began decades ago; however, its understanding is generally not comprehensive. Moreover, it is necessary to organize research resources and concentrate on key technological developments to make breakthroughs the soonest possible.

4.1 Forward design technologies of EMP protection

A major infrastructure generally involves integrated circuits, printed circuits, modules, and other basic devices/equipment, which show EMV characteristics in a high-power EMP environment. Additionally, the error and damage effects caused by EMP events may also spread in the infrastructure network, making it extremely challenging to conduct protection work. From the development experience of system-level electromagnetic compatibility and EMP protection of various equipment, the efficient EMP protection of major infrastructure depends on quantitative design technologies. The key technologies include the following: (1) key design parameters for EMP protection, that is, the parameters for EMP protection demonstration, design, and testing. (2) Simulation models for the EMP protection. It is necessary to form high-fidelity models at the system level and develop dynamic simulation tools for the EMP effects. (3) Design method for the EMP protection. The quantitative design should allocate the key design parameters to different equipment of major infrastructure, and artificial intelligence tools may be useful for realizing the efficient design of complex infrastructure. (4) Design software for EMP protection. Regarding the specified requirements of EMP protection in major infrastructure, commercial software development and model verification of this software should be comprehensively conducted.

4.2 Infrastructure-level EMP equivalent testing technology

Major infrastructure is prodigious in architecture, and the effects of EMPs on such infrastructure are not fully understood. Additionally, destructive testing is extremely difficult to perform in real-world infrastructure networks. Equivalent testing technology is useful for solving the above problems and may include the following: (1) EMP coupling effects on antenna/wire ports. Understanding these effects can help create an EMV model for major infrastructure and further establish an evaluation model for EMP effects. (2) Dynamic response of EMP in major infrastructure to identify the coupling mechanisms of EMP in electromagnetic topology and capture the dynamic propagation characteristics of EMP-related faults. (3) Generation and injection methods for EMP in major infrastructure. Models must be accurately scaled in the time/space/frequency/energy fields to realize the equivalent verification of EMP effects.

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4.3 Monitoring of EMP events at a large scale

Major infrastructure is widely distributed throughout the country, constituting an ultra-wide area, multilevel complex network. EMPs act on major infrastructure but does not leave any apparent traces. Hence, it is difficult to clarify the source of infrastructure failure, which makes it more difficult to repair these faults without useful information. Building a highly efficient and low-cost EMP threat monitoring system is an effective solution for these problems. The main components include: (1) EMP monitoring, which requires technology breakthroughs in low-cost miniaturized antennas, acquisition circuits, and data storage methods; (2) intelligent identification of EMP, which can help identify typical characteristics of EMP signals, forming an intelligent EMP identification tool; (3) wide-area EMP data processing; with the distributed/centralized Internet of Things, a wide-area EMP threat monitoring system can be created, and (4) an early warning system for EMP events. It is useful to build information transmission and sharing mechanisms for EMP threat early warning purposes and to develop artificial intelligence, big data prediction, and other technologies. This can improve the monitoring and early warning capabilities of EMP threats.

5 Current state and existing challenges of non-nuclear EMP protection of major infrastructure in China

5.1 Research is relatively scattered

China's scientific research effort on the electromagnetic security of major infrastructure is relatively scattered as there is a lack of scientific research institutions specializing in this field. Therefore, subject disciplines in related fields have not been established, and the layout of major science and technology projects at the national level has just begun. Owing to the lack of national scientific research institutions specializing in electromagnetic security research, the technical strength in this field is not strong. Additionally, design methodologies, experimental evaluations, and decision assistance exhibit obvious weaknesses. Quantitative design software, electromagnetic security testing apparatuses, evaluation methods, related database of key infrastructure, electromagnetic models of integrated circuits, and others, are not sufficiently available.

At present, China's industry research institutes, such as the China Electric Power Research Institute, China Institute of Information and Communication Technology, and China Railway Signal and Communication Institute, have finished lightning protection technologies for the infrastructure to improve the lightning protection design of electric power grids, communications, and high-speed railways. However, industry research institutes have insufficient personnel allocation in the field of electromagnetic security, and personnel in related businesses do not have these activities as part of their main job responsibilities. Therefore, these institutes are often unable to invest sufficient resources in fundamental research in this field.

Existing international experience shows that establishing an integrated research system with national laboratories as the core is an effective way to solve the science and technology challenges that exist in the electromagnetic security of major infrastructures. In contrast, China's investment in the EMP protection of major infrastructure is insufficient, and multidisciplinary collaborative research is scarce. The independent development of key software and hardware can still be enhanced, and the engineering management of EMP protection still has room for improvement. The current capability is not sufficient to support the EMP protection project of a highly complex, wide-area, and heterogeneous major infrastructure.

5.2 Core protective devices do not match first-class levels

Core protective devices are the foundation for supporting the EMP protection of major infrastructure, and the implementation cost of infrastructure protection is relatively high. This industry has considerable potential for future development. Moreover, the EMP protection industry has a high scientific and technological content, which is suitable for the country to vigorously expand the industry. China has a certain technical foundation in this field that can strengthen top-level planning and resource integration to achieve rapid development.

The core protective devices can be divided into multiple levels (Fig. 4), and the corresponding EMP protection capability should be improved step by step; that is, to meet the next level of electromagnetic protection, the level should automatically comply with the former level of protection. (1) Level 1 protection is mainly focused on the storage of the key components and spare parts of the infrastructure to prevent all types of high-power EMPs from affecting the security of the electromagnetically vulnerable devices. (2) Level 2 protection will efficiently improve the electromagnetic security capability of major infrastructure, including surge protection, filter protection, and uninterruptible power supply. Level 2 protection devices may be a future industrial direction for China to focus on. (3) Level 3 protection is mainly used for printed circuits and is applicable to all types of transient suppression devices, such as gas discharge tubes, metal oxide varistors, and transient voltage control diodes. When facing nanosecond EMP or HPM pulses in the high-frequency range, existing devices cannot provide sufficient protection. This is an immediate industry development goal for the future.

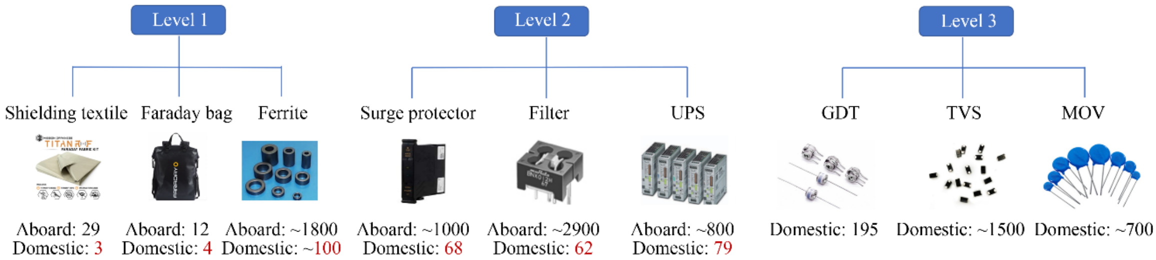

Fig. 4. Commercial products for EMP protection.

Note: UPS refers to uninterrupted power supply; GDT refers to gas discharge tube; TVS refers to transient voltage suppressor; MOV refers to metal oxide varistor. The data abroad are sourced from Mouser and other platforms, while the domestic data are sourced from Mouser and Alibaba; data was collected in December 2021.

6 Strategy for the non-nuclear EMP protection of major infrastructure in China

6.1 Strengthening governmental leadership

The high-power EMP protection of major infrastructure requires a top-level management organization to be established to coordinate administrative departments, enterprises, research institutes, universities, and social forces. With reference to the organizational structure in the field of national security, an electromagnetic security system for major infrastructure is proposed (Fig. 5). Under the unified organization of the leading organization, monitoring, emergency management, and coordination systems, as well as an expert committee must be established to focus on security management, security technology, and security operation systems.

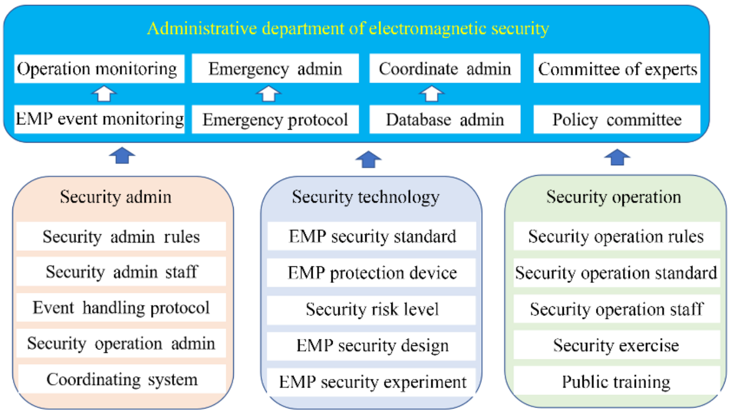

Fig. 5. Electromagnetic security system for major infrastructure.

It is appropriate to learn from developed countries for the successful implementation of the organizational and operational improvements, which will promptly strengthen the weak links such as policy, management, law, and technology. Country-wide emergency early warning, emergency communication, and emergency management systems should be established.

6.2 Organizing scientific research

The EMP protection of major infrastructure involves society and many industries. Therefore, it is necessary to concentrate on the major scientific and technological issues. It is suggested that major national science and technology projects must be implemented, and research on key science and technology problems, such as the underlying physics of EMP effects, system security architecture, key weak area protection, and infrastructure-level tests and evaluation, must be conducted. These suggestions aim to explore the degree of correlation between major

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infrastructure and production, business, finance, economy, and citizen life and clarify the impact mode of facility failures on social stability.

Power grids, high-speed railways, and mobile communications have become China's "name cards" and related products have a comparative advantage in the international market. They have strong competitiveness and relatively high economic output values, which are the top priorities of scientific research in the subdivision field of major infrastructure. This focus is aimed at improving the security level of infrastructure in related fields and to further create a good international image of China's industrial products.

6.3 Publishing standards and specifications

The high-power EMP protection of major infrastructure is a concrete engineering practice in various industries. There is an urgent need to establish protection standards and specifications adapted to meet national conditions. The key to the establishment of relevant standards and specifications lies in "knowing yourself and your enemy". "Knowing yourself" refers to the basic information and data of the electromagnetic security of major infrastructure, and clearly identifies weak links, damage threshold, and damage effect. "Knowing your enemy" analyzes the existing characteristics of non-nuclear EMP sources and predicts the long-term development trend of EMP sources, especially how EMP affects infrastructure.

The publication of relevant standards and specifications still needs to be emphasized. Good cost-effective protection technical standards and current situation detection methods should be developed for the EMP protection of existing infrastructure. EMP protection standards and technical specifications for new infrastructure must be clarified in the future. Additionally, the early warning mechanisms and resilience strategies for EMP events must be actively explored.

6.4 Stimulating the vitality of industry

The protection of major infrastructure against high-power EMP is a complex management and engineering problem, and economic cost plays a key role in the success of engineering practice. Therefore, to support the development of EMP protection for major infrastructure, it is appropriate to fully stimulate the vitality of the industry and provide reasonable financial and preferential tax policies. Additionally, it is suggested that independent research and the development of electromagnetic protection core software, protective modules, and protective devices must be supported to promote the formation of new strategic emerging industries, and steadily realize the export of high-technology products.

6.5 Implementing the protection work in stages

According to the technical system and standards in relevant fields, the protection rating of major infrastructure and coordination of important tasks must be performed. The implementation of EMP protection must start with infrastructure with a higher priority.

The protection and reinforcement plan of the infrastructure should be formulated according to the different stages of planning, construction, operation, and maintenance of major infrastructure. It is recommended that new infrastructure should be designed and verified according to the relevant standards. Existing infrastructure can be combined with facility maintenance and overhaul processes, mainly to reinforce important subsystems.

It is suggested that the characteristics of the power supply, communication, and personnel support systems of major infrastructure should be analyzed. The coordination, planning, and building of a private network system covering the entire country should be conducted to maintain the resilience of major infrastructure under extreme conditions.

6.6 Promoting talent cultivation

The EMP protection of major infrastructure spans the disciplines of engineering, mathematics, management, economics, and other disciplines, requiring interdisciplinary and comprehensive talent. However, China currently lacks human resources with relevant knowledge. Scholars and engineers in this field require a deeper understanding of mathematical foundations. To accomplish this, systematic electromagnetic courses, excellent teaching and experimental conditions, and a practical platform must be provided.

Apart from a few "double first-class" construction universities and disciplines, the current number of electromagnetic courses in many universities has been dramatically reduced. Therefore, the number and quality of students in this field is insufficient. Therefore, there is an urgent need to actively explore and form a training system for electromagnetic security specialists in the existing discipline system. These suggestions will establish an electromagnetic security discipline in a timely manner.

6.7 Reinforcing public training

The daily lives of citizens depends on major infrastructure, and failures of major infrastructure will inevitably affect the lives and production activities of citizens. It is suggested that the lessons learned from the advanced experience of earthquake emergency avoidance work should be implemented to strengthen public knowledge. The training should encompass the "before," "during," and "after" to reasonably enhance public risk awareness. If any extreme events occur, public training may minimize public panic.

Various methods can be adopted to reinforce public training, such as setting up an "infrastructure security day", carrying out various emergency exercises, and steadily improving public awareness, emergency response, and self-rescue capabilities.

7 Conclusion

This study analyzes the threats of non-nuclear EMP on major infrastructure and proposes targeted protection strategies based on national conditions. The research content broadly covers power grids, transportation, communication, and other infrastructure, and is expected to be scientifically implemented in future major engineering practices. Power grids have always been a common key link for ensuring the safe operation of various major infrastructures and can be regarded as the foundation of major infrastructures. In the context of energy transformation, the openness and complexity of the power system are constantly increasing, and the operational risk under the threat of potential extreme events is rapidly increasing. Therefore, this industry could take the lead in implementing a demonstration project for protecting the power system against a strong EMP, and the effective response of strong non-nuclear EMP threats should be adopted as the core goal of the demonstration project.

China could rely on new infrastructure to perform testing and verification during the implementation process. Social forces and capital participation could be leveraged to quickly resolve scientific, technical, and engineering problems. Standards and specifications should be promptly summarized and published, and protection technologies must be gradually promoted and applied to existing infrastructure. Prospectively studying the threat source characteristics, propagation law, and action mechanism of non-nuclear EMPs and mastering the weak nodes and sensitive equipment of the power system under the action of EMPs will improve the basic theory and lead to technical breakthroughs. The propagation path and influence law of the EMV must be clarified and the EMP action mode and scale grade of the power system must be predicted to develop electromagnetic protective components, modules, and devices, and enable the rapid recovery technology of vulnerable devices/cards/equipment in the power system.

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