Assessing Power Grid Resilience to Electromagnetic Weapons of Massive Destruction

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Dedication

I would like to dedicate my thesis to my parents who always fully supported me in high education.

Acknowledgments

I would like to express my sincere gratitude to my advisor, Prof. Payman Dehghanian, for his understanding, wisdom, patience, encouragements, and for pushing me farther than where I thought I could go. His guidance and feedback helped me in all the time of courses, research and writing of this thesis. I also want to thank to my friends and the GW SmartGrid Laboratory members, especially Dingwei Wang, Shiyuan Wang, Yifu Li, Mostafa Nazemi, Jinshun Su, Chengzhi Xie and the department faculty and staff for making my time at George Washington University a wonderful experience in a healthy and friendly environment. Most of all, I am fully grateful to my parents for terrific supports, which are more than words can describe.

Abstract

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Nowadays, the power grid is becoming more efficient and intelligent. Internet technology and many electronic components composed of automation equipment is used in the power grid. However, with the increasing complexity of the power grid system, the power grid's vulnerability is also increasing. As the most significant and most interconnected infrastructure, the power grid is highly vulnerable to damage from both nature and human beings. The power system is a vast system not only in scale but also in regional span. Minor disturbance and destruction will not cause severe consequences to the whole dynamic stability. However, it is not that there are no means of striking a wide area of the power grid, and a nuclear electromagnetic pulse is an important one. Because of how the nuclear EMP is generated, the electrical and electronic equipment in the power grid exposed to the earth's surface will be subjected to the impact of the nuclear EMP. Moreover, the attack of a nuclear electromagnetic pulse on power grid equipment is likely to be devastating, so it is necessary to formulate a reasonable power grid flexibility strategy for nuclear electromagnetic pulse.

This thesis first focuses on the causes of nuclear EMP and the characteristics of its pulse waveform and introduces some existing protective measures against electrical equipment in the power grid. Then CST studio is used to simulate the electromagnetic pulse of the transformer and analyze its fault characteristics, and the harmonic components of the transformer were analyzed by using the saturation transformer inrush current model. The 30 bus system is used to simulate the electromagnetic pulse of the

whole power grid and analyze the fault causes of the power grid through the power flow and electromagnetic induction current. Finally, a feasible resilience strategy is proposed based on the above fault analysis results.

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Chapter 1: Introduction

1.1 Problem Statement

In modern society, as the basis of human production and life, the power system's operation safety is essential.[20, 29, 30] The power system as infrastructure is inevitably widely distributed, which means that it is vulnerable to various external attacks, which may come from natural and human-made.[86, 87, 101, 105, 113, 117–119, 126–128] Weapons quickly attack the power system because of its wide distribution and high economic value.

With the development of weapon technology, targeted military strikes on power systems are also improving. The different attack means can be roughly divided into network soft killing and hard military destruction.[6, 8, 11, 112, 124] Military hard destruction means using conventional or special military weapons to carry out direct physical strikes against power facilities. During World War II, large-scale Allied bombing of German power generation facilities shut down German industrial facilities. In the Kosovo war in 1999, NATO destroyed more than 80% of the electricity and oil, and other energy targets of Yugoslavia through 78 days of bombing, and also used graphite fiber bombs especially to destroy the power grid, resulting in a wide range of power outages in the Yugoslavia, which directly affected the process and outcome of the Kosovo war.[35, 45, 61] However, such a direct strike is limited in the face of a decentralized grid of power hubs. In World War II, Germany's 1.4% of power plants generated 51.1% of its electricity. Over the same period, a large number of small and scattered power plants supply 75% of Japan's electricity. A different feature of the power hub makes the Allied think that destroying Japan's electric power supply is hard to accomplish. Network soft killing uses the hacker attack to get the power system's control power and indirect use of electrical equipment to create serious accidents. With the smart grid development, the technology of network is used in the supervisory control power grid. The network application allows cyber attacks to attack large areas of the power grid regardless of geographic constraints.[17, 103] Compared with the network soft killing, regulation military hard destruction seems easy to defend, especially for the power system with adequate generation back-up and excellent emergency repair capacity. However, an Electromagnetic Pulse attack can affect a vast range of electrical devices, which ignores the limitation of geographic constraints.[100]

Electromagnetic Pulse(EMP) is some severe electromagnetic energy bursts with a unique range or spectrum of frequencies present, pulse waveform, and energy type. Electromagnetic pulses can be generated in several ways, such as electrostatic sparks, interference from gasoline engine sparks, lightning, electrical switches, geomagnetic disturbances (GMDs) caused by coronal mass ejections (CMEs), nuclear EMP, and non-nuclear EMP weapons. This thesis focus on the atomic EMP. The EMP weapon has a flexible strike range depending on the weapon's performance. Depending on the intensity, an electromagnetic pulse from a nuclear weapon can affect power system equipment within a radius of 40 to 400 kilometers. It affects 70% of the U.S. power grid. An EMP weapon's impact is much more significant than that of a conventional weapon, approaching or even surpassing the effects of a large-scale natural disaster on the power grid.[100] So if the power system cannot prepare, if the power system fails to formulate a plan that defends the EMP strike, the nuclear EMP accidents could result in a nationwide blackout similar to Texas.[16]

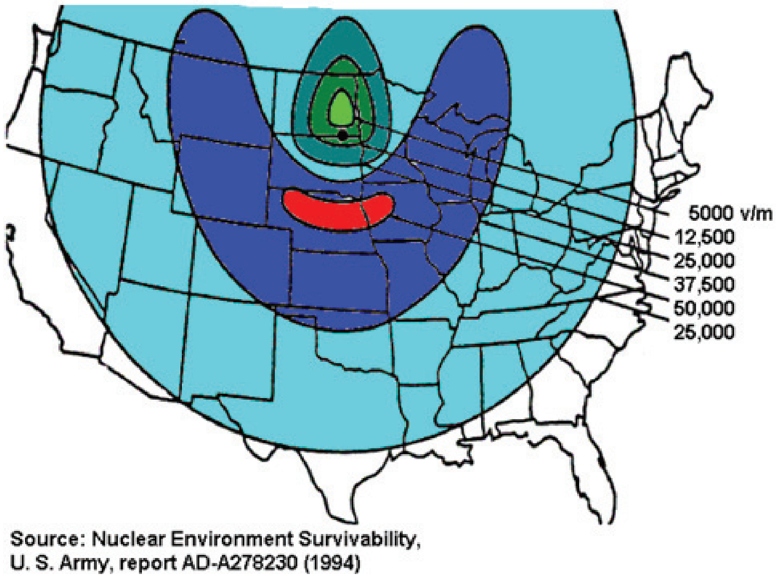


Figure 1.1: The Strike Range of Nuclear EMP Weapon

The effects of nuclear EMP are mainly from high-altitude EMP. High-altitude EMP(HEMP) sources tend to erupt at altitudes over 30 kilometers, so the high temperature, explosions, and radiation damage caused by conventional nuclear bombs would not affect ground equipment. Also, because of HEMP sources' altitudes, with the vast effect range of atomic EMP, EMP's damage cannot be defended by the geographic constraints. High-altitude EMP will cause severe damage to power generation equipment, transmission equipment, control equipment, communication equipment, etc.

1.2 The resilience of power system

The resilience of the power system can be defined in three parts[75, 91]:

1. The power system should withstand disasters effectively: The power system is accompanied by a series of conventional low hazard risks, such

as load changes, harmonics, and other influences on the power system transmission quality. However, the power system resilience strategy solves the power system accidents with high-impact low-frequency(HILP) incidents.[91] These accidents often result in large-scale failures of power system equipment, leaving power systems in a state of paralysis. These accidents often lead to large-scale power system equipment failure and power system paralysis, so protection against these accidents is essential.

2. In the event of HILP incidents, as much as possible should be done to ensure the supply of power systems and maintain critical infrastructure and social services. In February 2021, three severe winter storms attack the power system of Texas.[16] The lack of response to the Texas power system's ice storm has prevented power supplies from being restored for a long time. Seventy people died, and at least 300 carbon monoxide poisoning cases occurred because of heating problems caused by power shortages. A shortage of electricity in shops has caused a severe shortfall in food supplies. Stopping the fossil fuel infrastructures causes harmful gases(sulfur dioxide, natural gas, carbon monoxide) to leak. The shortage of electricity supply caused a series of secondary losses, so ensuring basic power supply is an important goal of power system flexibility strategy.

3. When the HILP incidents severely hit the power system and even lose the power supply capacity, the power system resilience strategy should make it possible to quickly recover to the normal operation state during or after the disaster. To reduce the losses of economy and life, restore power supply in the power area to utilize timely emergency repair and dispatching.

Based on the three parts of the power system resilience and the feature of the HILP incidents, the strength of the power system will undergo the following changes:

1. Power system with suitable HILP incident protection measures and troubleshooting strategies: The power system's resilience is slow to decline in the event of a disaster due to adequate defenses. As the resilience level reaches the warning line, the monitoring device sounds an alarm, and troubleshooting measures begin to work. The resilience of the power system will be restored. There will be no power shortage in this power system, and the user experience on the load side will be the same as in regular operation.[24–26, 28, 44]
2. Power system with HILP incident conventional or minimum protection standards and troubleshooting measures: The power system's resilience level will be similar to the first type of power system. However, due to the decline of the power system's protection ability, the drop of the power system's resilience level will be faster, making the power system have a power outage accident in the face of extreme disasters.[5, 39, 81, 83, 92, 93, 98, 99]
3. Power system with unsuitable HILP incident conventional and troubleshooting measures: The power system's resilience level will decrease rapidly, and power cuts will happen quickly. At this time, the emergency repair of the power system will be essential. Part of the power grid can be cut off appropriately to protect critical equipment from damage, to achieve the purpose of quick restoration of power supply after the disaster.[19, 21–23, 27, 93]

1.3 Thesis Outline

In this thesis, the resilience strategy of the power grid under the EMP attack will be discussed. The thesis will focus on the basic theory of EMP, EMP protection of electric devices, the interference and fault that electromagnetic pulse strike may bring to the power system, and how to solve it.

Chapter 2 is a literature review of EMP. It will introduce the basic knowledge and theory of nuclear EMP attacks, such as EMP damage and result. Also, this chapter will introduce the experimental history of EMP and the EMP protection measures for some electronic equipment used in power systems to provide the preconditions for resilience strategies.

Chapter 3 provides the EMP attack simulation of the transformer. An ordinary dry-type transformer is used for electromagnetic pulse simulation to observe the transformer's electric field and magnetic field changes. The transformer short circuit model simulates the excitation inrush current experienced by the power transformer under the attack of EMP to determine the transformer fault. Chapter 4 provides the EMP attack simulation of a power system. With the GIC model of the power world software, IEEE 30 bus system will be attacked by EMP. The attack process will be represented by a diagram of the induced current variation, while the impact of EMP on the power system will be represented by reactive power loss and line load.

In Chapter 5, the harmonic of transformer caused by EMP, reactive power loss of saturated system and unsaturated system, and line overload are discussed. By adjusting the simulation model to find the solution and comparing the changes before and after the adjustment, the power system's resilience strategy under EMP attack is obtained. Continue to adjust the location of nuclear EMP explosions to clarify that the same system in the face of different strikes in the way of response needs to change. This provides a machine learning model for and EMP injury prediction and resilience strategy formulation. At the same time, in order to provide enough learning data for machine learning, a simulation database example is made. Some ongoing studies that may be helpful to EMP resilience defense strategies in future power systems are also introduced

Chapter 6 will get the conclusion of the resilience strategy of the power grid under the EMP attack. Simultaneously, The assumption of the elastic strategy of nuclear electromagnetic pulse resistance is introduced step by step.

Chapter 2: Literature Review

2.1 Introduction

The EMP attack is a complex process with the different waveform of the electromagnetic pulse and gives different attacks to electronic devices and electric devices. Nowadays, in the power system, electronic equipment plays a crucial role in the control and monitoring of the power grid. Therefore, the power system must ensure the regular operation of power electronic equipment to protect the power equipment through reasonable actions. This chapter will introduce the theory of the nuclear EMP, the simulation history of EMP, the protection of the power electronic devices, and the EMP's damage.[40, 100]

2.2 Nuclear EMP

A nuclear EMP is a disaster caused by the explosion of a nuclear weapon at a high altitude, also can be called high-altitude EMP(HEMP). When the high altitude nuclear detonation happens, the nuclear weapon will release a short gamma rays pulse. The gamma rays are similar to the X-ray, but the gamma rays' photon has higher energy than the X-ray. These photons flow in the explosion's direction, some of them descending towards the lower altitude, and the gamma rays also travel towards the lower altitude. The gamma rays start striking the air molecules and produce a lot of Compton electrons by depositing energy. The Compton electrons are trapped by the magnetic field of the earth and produce the oscillating current. The EMP is a kind of electric-magnetic field rising caused by the oscillating current.

That EMP always happens on the 20 to 40 kilometers in the air.[37, 54]

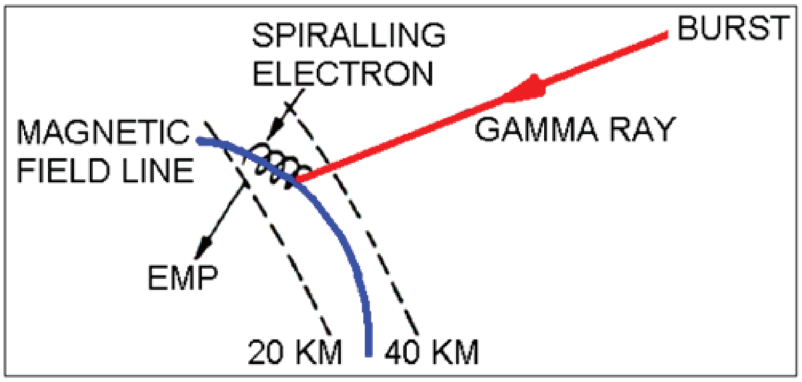


Figure 2.1: The Theory Of Nuclear EMP Generation

Scholarly research separates the EMP waveform into three parts: E1 wave is the first part of the waveform, also can be called early time HEMP. The duration of E1 waves is in sub-nanoseconds, up to a microsecond; E2 wave, or intermediate wave, lasts from a microsecond to a nanosecond; E3, or late-time EMP covering environments later than one second.[40]

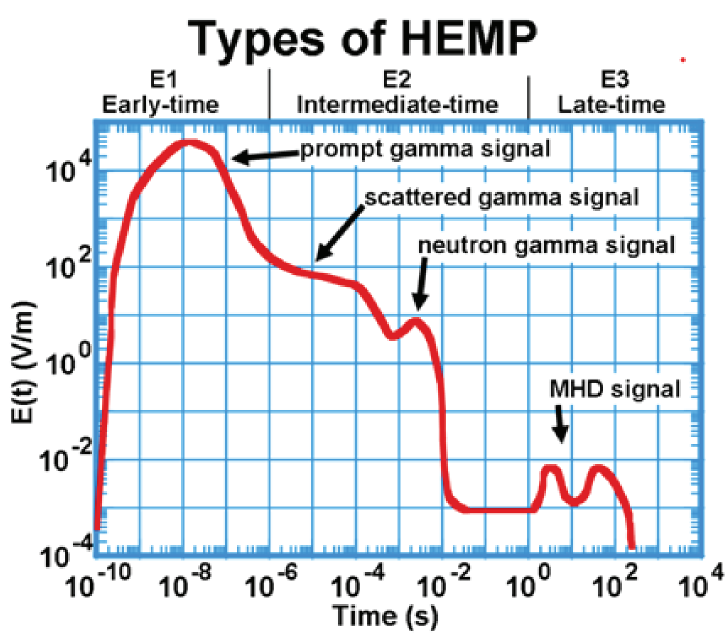


Figure 2.2: The Waveform Of HEMP Wave

1. E1 wave: The E1 wave is the shortest duration of the HEMP waveform but has the most substantial energy release. Because of this property, the electric field changes generated by the E1 wave are intense and short, developing strong pulse consist of high voltages and surge current in the electrical conductors. The E1 wave can destroy electronic devices, and the regular and the electric field change so quickly, standard surge protection method cannot be used in the E1 defense. The only equipment that can promptly respond to surge current can play its due role. In addition to being a powerful pulse, the E1 wave also has a wide range of coverage. Figure 1 shows the impact range of the E1 field and shows the peak E-field strength of the E1 wave. E1 waves are usually thought to erupt at altitudes of more than 30 km.[100]
2. E2 wave: The scattering gamma rays and producing neutrons by producing inelastic gamma rays generate the E2 waveform similar to the lighting. The pulse strength of the E2 wave is less than the lighting strike pulse. Generally speaking, the E2 pulse strike is the easiest to protect the power system because the lighting protection devices are the power system's regulation components.[114]
3. E3 wave: Compare with the E1 wave and the E2 wave, the energy-releasing of the E3 wave is more slowly and slightly. The E3 wave is caused by the distortion of the geomagnetic field generated by the ionized atmosphere's motion through the geomagnetic line and the weapon debris from the nuclear explosion. The E3 wave is similar in origin to the Geomagnetic Pulse, caused by solar wind and geomagnetic field interaction. The damage of the E3 wave is the same as the Geomagnetic Pulse damage created by the geomagnetically induced current(GIC), which can cause severe problems on the power transformer. The duration

of the E3 wave is longer than the E1 wave, and the E2 wave is related to the motion time and occurrence height of the source of the E3 wave. The E1 and E2 waves are both directly or indirectly caused by gamma rays, and the gamma rays' energy in a nuclear blast is only 0.1%. The kinetic energy, which supplies the weapon debris's motivation energy, occupies 25% of the whole energy. The electromagnetic pulse from the E3 wave will be maximized at an altitude of 130 to 500 kilometers, well above the E1 wave burst height. Therefore, the high kinetic energy of the weapon debris combined with the high action height enables them to move at high altitudes for a long time and distort the geomagnetic field so that the duration of the E3 wave is much longer than that of the E1 wave and E2 wave. The E3 wave usually lasts 10 to 30 seconds.[40]

Energy Fractions of Burst			
Type	Typical Percentage	Source	Typical particle energy
X rays (photons)	70	Atomic processes - electrons	10 keV
Kinetic energy	25	Thermal	-
Neutrons	1	Processes in Nucleus	0.01 – 15 MeV
Gammas (photons)	0.1	Nucleus	0.1 - 5 MeV

Figure 2.3: The Typical distribution of energy from a HEMP

2.3 The Damage of Nuclear EMP in power system

Since the nuclear EMP pulse covers several kinds of the electrical field, the Nuclear EMP's damage in the power system is comprehensive and destructive. In the E1 wave stage, the powerful short pulses can cause electronic equipment to be subjected to a voltage exceeding the breakdown voltage, causing irreversible damage to the electronic equipment and crippling electrical system communications, automatic control equipment, and some lightning protection equipment.[38, 55, 77] Because the E1 wave could destroy part of the lightning protection of the power grid and the E2 wave is similar to lightning strikes on the power grid, the E2 wave would create inrush currents in transmission lines that would generate high voltages through line resistances. Since the power system out of control under the E1 wave strike, the power system will not be able to protect itself from emergency power cuts. The waveform of the E3 stage will produce a low amplitude pulse that lasts for 10 seconds to 100 seconds. Moreover, this pulse can induce a high-level current in the transmission line and cause damage to electrical devices such as the transformer in service.[46, 48, 56]

2.4 HEMP Simulator

Since the signing of the nuclear test-ban treaty in 1996, many countries have begun to build EMP simulators for the nuclear attack. Because the E1 wave will cause damage to the electronic sensing equipment in the monitoring control and communication system, and it is difficult to protect this equipment in the close-range test, the simulation experiment is mainly to simulate the impact caused by nuclear electromagnetic pulse. The HEMP simulation experiment usually consists of a high voltage pulse source and an antenna system for generating electric field pulses of variable strength.[55]

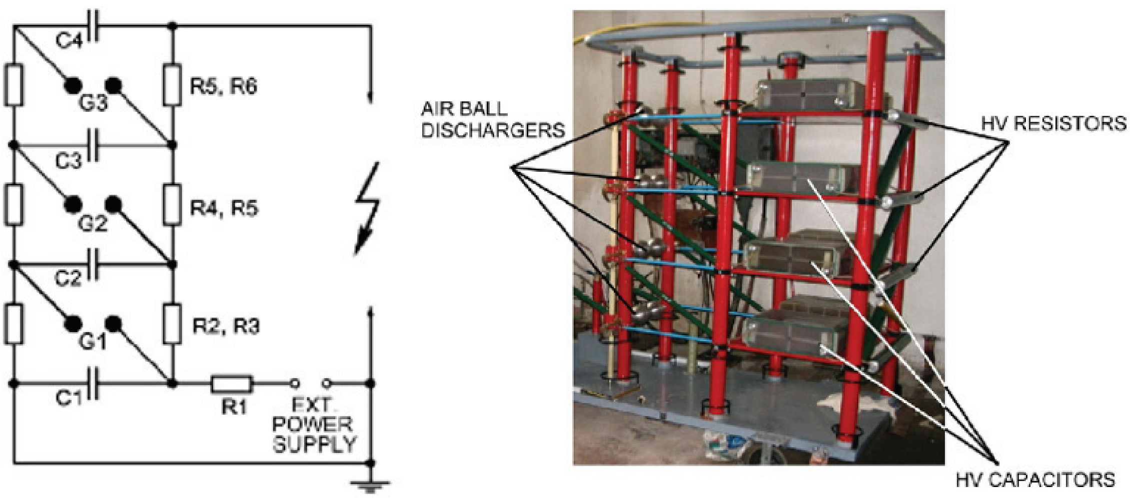


Figure 2.4: High-voltage Source

The High-voltage source usually consists of high-voltage capacitors(C1-C4 in Figure 4) in parallel and the controlled discharged tubes(G1-G3). First, the control discharge tube is in the open circuit, and the capacitor is in parallel while the external power source charges the capacitor. After charging, the external power supply is stopped, and the control discharge tube is closed. At this time, the capacitor is in a series state and discharges at the electrode.[55]

Dr. Carl Edward classified the HEMP simulators into three types: guided-wave, dipole, and hybrid. The Guided-wave HEMP simulators are the simplest simulator, have only the basic antenna and high voltage generator.[34, 42, 60] The upper antenna of the device is suspended by a plate stretching above the experimental equipment and supported by thermal insulation material, while the lower antenna is embedded in a concrete "plate." This setting creates a vertical electric field. However, this device makes the ground reflection waves can not affect the experiment, which makes the simulation of the ground equipment more distorted.[60]

Figure 2.5: Guided-wave HEMP Simulator(left) And Dipole Simulator(Right)

The second dipole HEMP simulator relies on waves reflected from the ground and water as incident waves. The dipole simulation does not require the subject to be in the center of the pulse-generating device.[76, 94**?**] The subject can be placed next to the simulator because the reflected wave will be closer to the nuclear explosion's pulse distribution so that the dipole simulation experiment can be simulated in both vertical and horizontal directions. Still, the reflected wave, so the pulse energy conversion is lower.[65, 123]

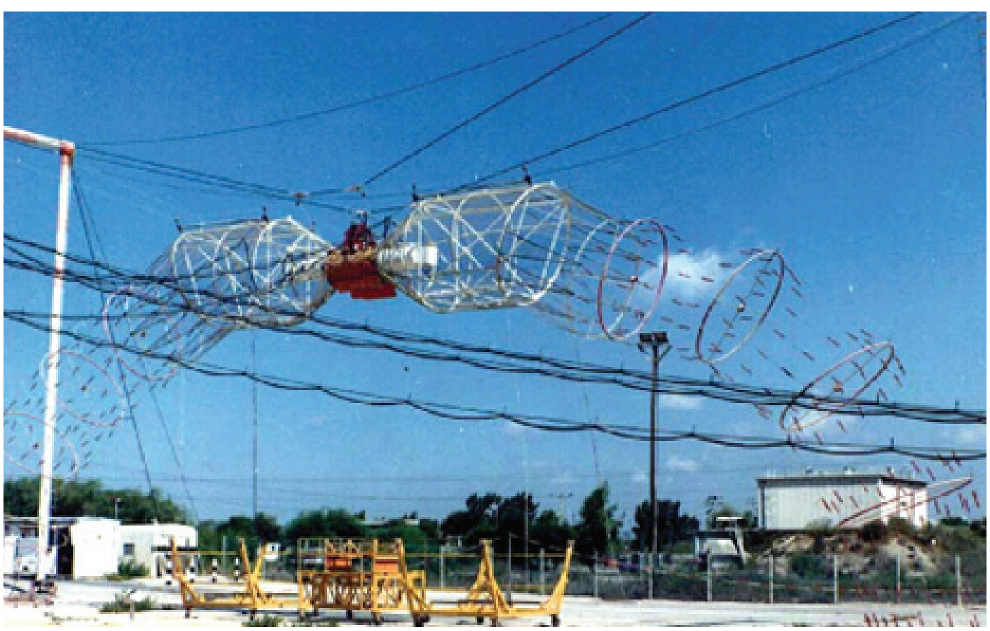


Figure 2.6: Hybrid HEMP Simulator

The hybrid simulators are used to do the E1 wave, and the ground face reflects wave simulation.[15, 33, 72**?**] The simulator consists of a centrally located generator and radiating cylindrical barrel antennas spanning it from the air from both sides. This simulator's pulse source is located on the ground, limiting its capacity much lower than the previous two types of simulators.[15, 71]

2.5 The protection of the electronic components

There are two kinds of protected electronic components in the power grid: the front-door coupling devices and back-door coupling devices. The front-door coupling suffers the strike of the external electromagnetic radiation directly. The back-door coupling suffers the indirect entering strike of the external electromagnetic radiation through the back door, which is the defense method's gap or input from the system. The electronic equipment is protected by the cabinets and buildings, which can impair the strike of external electromagnetic radiation. The back-door coupling will be the main problem of the electronic defense of the power grid.[43, 59]

Firstly, the concept of the protection component response time of the power system should be defined. The protection component response time is the period between the time when an overvoltage pulse is applied to the protection element to trigger the protection element to the time when the overvoltage protection component cuts off the pulse. The shorter the response time of the protection component, the better the electronic equipment's ability. In figure 2.7, the surface-mount varistor successfully limits the pulse peak's amplitude during the reaction time.[4, 52, 57, 63, 64]

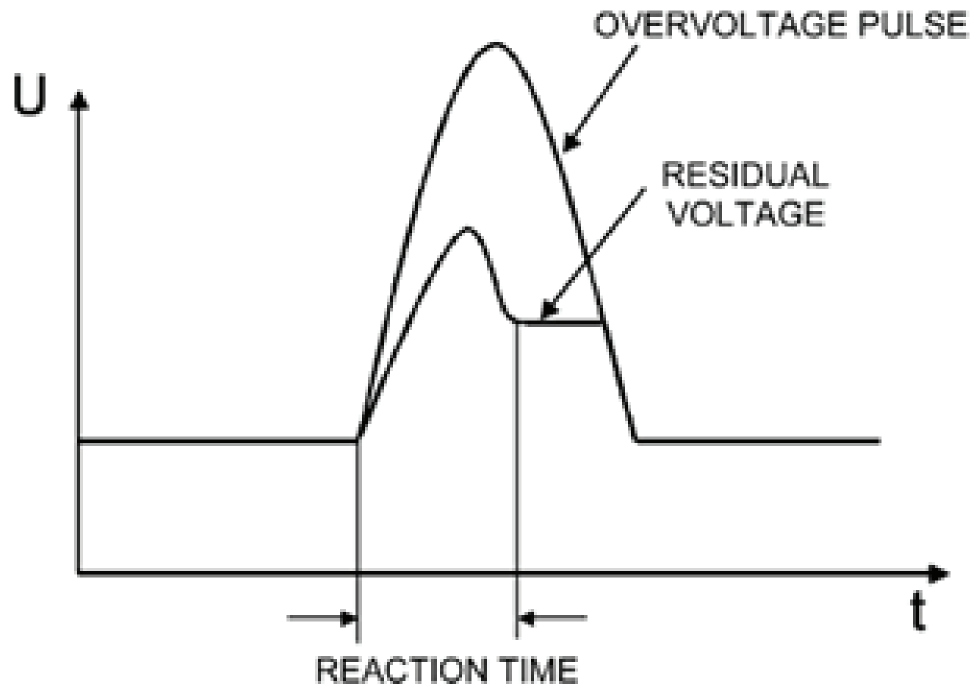


Figure 2.7: The response time of EV18N0402L surface-mount varistor

The development of the electronic components follows the principle: The higher the computing power of an integrated component, the higher the internal complexity, the smaller the size of its independent internal components, and the higher the density of the internal layout.[47, 49, 59, 104] Restrictions on the size of components and improvements in the internal spatial layout will weaken the internal components' insulation and external packaging layers.[9, 14] As a result, electronic devices need an external insulating layer to help protect them from HEMP damage. General, electronic equipment in the power system, such as digital protection relays(DPR), programmable logic controllers(PLC), automatic control equipment, power communication equipment, etc., are connected to the ground system and installed in a protective control cabinet.[49] Those cabinets are set in the relay room of the substation. The cabinets, relay room, and substation building can be treated as the insulation layer. Because EMP's high-voltage EMP can affect electronic devices directly. It can also affect sensitive electronic components directly through the interference grounding system through the protective layer. Therefore, it is necessary to build multi-layer protective measures outside the electronic equipment to achieve the multi-layer weakening of the HEMP pulse.

1. The HEMP defense of building: Since the electronics in the power system are not operating independently but are connected to the entire system, the adequate supply of HEMP to a single device is transmitted to other parts of the system. However, it is not practical for economic reasons to protect each device individually with HEMP, so it is more feasible to concentrate the equipment in a single building and retrofit the building with HEMP protection. According to the American National Institute of Standards and Technologies' research, reinforced concrete has the most substantial ability to reduce electromagnetic radiation among the standard building materials.[104] The parameters(moisture contents, type of the rebar, thickness, number of the layers, and the distance between the layer) of reinforced concrete also affect its electromagnetic shielding effect.[49, 104]

   Based on reinforced concrete's electromagnetic shielding characteristics, various additives are added to the concrete formula to enhance its electrical conductivity and enhance its electromagnetic shielding ability. Mainly used in concrete electromagnetic shielding additives are conductive powder (mainly graphite and metal), carbon wire, carbon nanotubes, and short steel wire.[102] However, this additive concrete has two disadvantages. Firstly, the mechanical strength of concrete will be significantly affected because the additive can account for 25% to 35% of the total weight. Secondly, the cost of this scheme is very high. Recently, in Russia, shungite is used as additives. Shungite is a natural mineral composite material consisting of fine-grained crystal silicate particles in an amorphous carbon matrix. A kind of mixtures material that consists of 26%-30% of carbon and 56%-60% of shungite can be applied in the electrostatic shielding of building materials.[47, 50] The price of this mixture material is close to the usual construction materials.

Building materials	**Attenuation, dB**	
	500 MHz	**1 GHz**
Concrete not rebar reinforced, thick:		
102 mm	7–11	11–14
203 mm	17–25	22–28
305 mm	31–45	33–45
Reinforced concrete wall, thick 203 mm:		
rebar dia. 19 mm, dist. between rebars—70 mm	26	30
rebar dia. 19 mm, dist. between rebars—140 mm	23	27
Concrete blocks with hollow cavities, thick:		
203 mm	8	12
406 mm	13	17
609 mm	26	28
Regular dry lumber, diameter:		
38 mm	2	3
76 mm	1.5	3
152 mm	4.5	6
Bricks, thick:		
1 brick (89 mm)	0	3.5
2 bricks (178 mm)	3.5	5.5
3 bricks (267 mm)	4	7

Figure 2.8: Electrostatic shielding capability of conventional building material

Based on reinforced concrete's electromagnetic shielding characteristics, various additives are added to the concrete formula to enhance its electrical conductivity and enhance its electromagnetic shielding ability. Mainly used in concrete electromagnetic shielding additives are conductive powder (mainly graphite and metal), carbon wire, carbon nanotubes, and short steel wire. However, this additive concrete has two disadvantages. Firstly, the mechanical strength of concrete will be significantly affected because the additive can account for 25% to 35% of the total weight. Secondly, the cost of this scheme is very high. Recently, in Russia, shungite is used as additives. Shungite is a natural mineral composite material consisting of fine-grained crystal silicate particles in an amorphous carbon matrix. A kind of mixtures material that consists of 26%-30% of carbon and 56%-60% of shungite can be applied in the electrostatic shielding of building materials. The price of this mixture material is close to the usual construction materials.[47, 50]

Frequency range, MHz	3–30	30–300	300–1200
Attenuation, dB	6–10	8–14	12–16

Figure 2.9: Electrostatic shielding ability of shungite mixed reinforced concrete

The University of Nebraska in the USA provides another kind of electromagnetic shielding reinforced concrete formula. Moreover, this particular material is called EMB3. Taconite, which contains 23% of the mixture, is a ribbon of iron. Compared with the same type of material, the cost of this material is reduced by 60%.[**?**]

In addition to doping the concrete with electrostatic shielding material, the building interior can be covered with copper electrostatic layers to protect or use unique building materials for building construction, but this protection cost is too high.

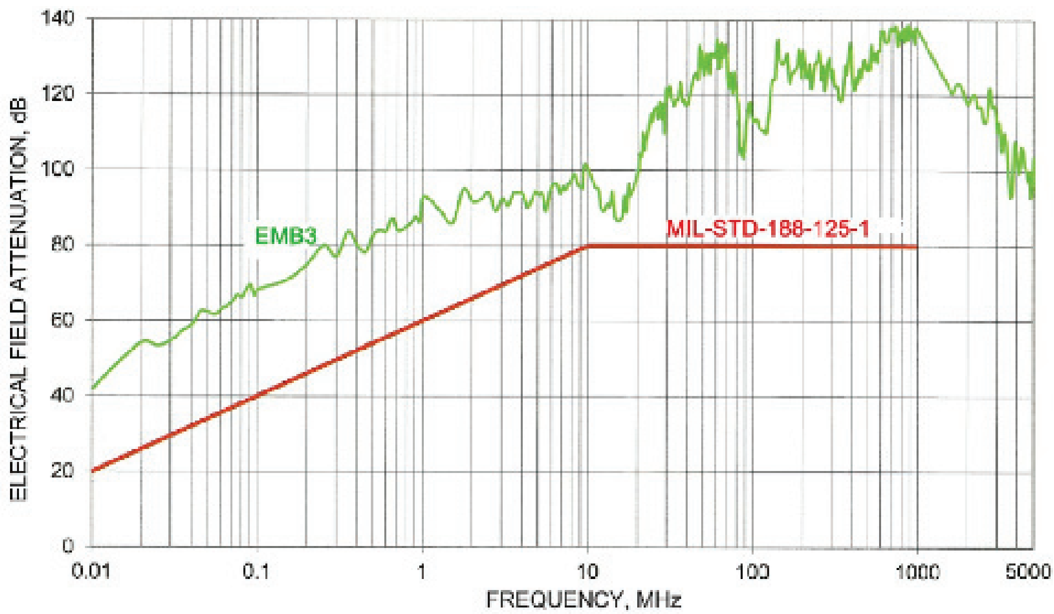


Figure 2.10: The feature of conductive EMB3 concrete (upper chart) being advertised and the requirements to shielding to ensure HEMP protection according to MIL-STD-188-125-1 standard

2. Grounding design in HEMP strike: The primary reason for providing grounding for electronic equipment is to provide a stable reference location for measuring signals and supply voltages and protect the equipment. Protection against EMP attacks is not a primary objective for grounding but can be considered a design factor.[74]

In the case of a nuclear EMP, however, the basic grounding system design would act like a guided antenna to the device to which it is connected. Although the soil's electrical conductivity can greatly reduce this effect, signals entering the system this way still pose a potential risk to the equipment. Usually, the ground line's impulse can be attenuated or transferred to the ground by adding a filter or other device to protect the overvoltage pulse between the ground line and the system. A unique floating ground design can isolate the power system from the surrounding conductive objects, thus effectively preventing electromagnetic pulse transmission. However, the standard floating ground design will cause isolated signal lines to generate static electricity, especially near high voltage lines.[53] Such static electricity accumulation is very likely and will cause the potential danger of electrostatic shock and electrostatic spark. In this regard, it is necessary to set up connected copper busbars on the insulators in all equipment cabinets and connect the equipment receiving insulation protection inside the cabinet with copper busbars. The copper busbars are related to the external grounding system through a high-voltage and high-resistance resistor to avoid spark accidents caused by static electricity on the cabinet surface.[1]

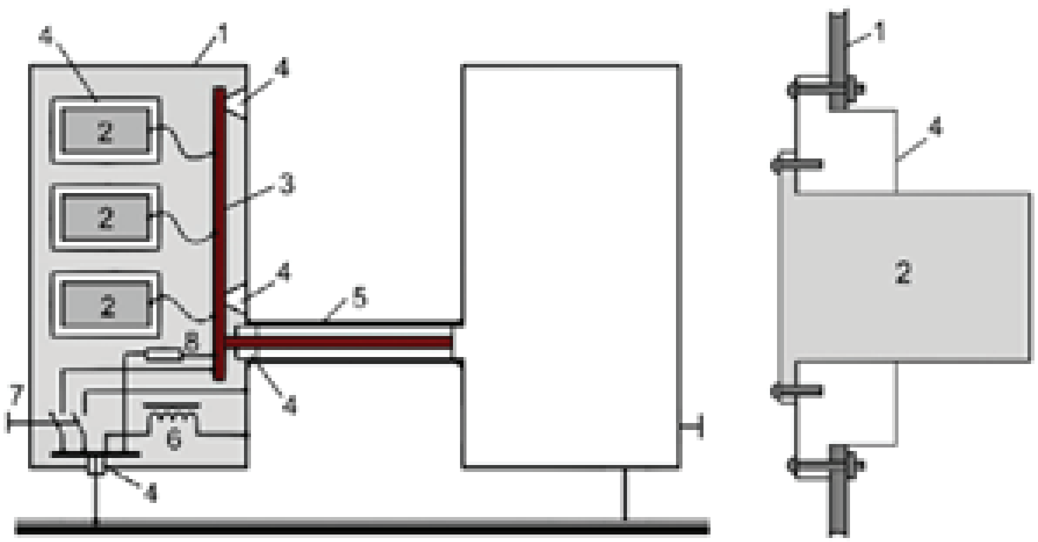


Figure 2.11: Example of a unique floating grounding system

Besides, the choice of the equipment cabinet can be made of steel plate without Windows and cracks. Although this cabinet has certain disadvantages compared with the glass door equipment cabinet during daily inspection and maintenance, it can significantly reduce the electromagnetic pulse.[3, 73] Simultaneously, galvanizing or using zinc primer on the steel plate can better help the equipment cabinet equalize the potential and thus strengthen the protection function of the equipment cabinet against electromagnetic pulse.

As for protecting the system's internal components, additional equipment such as filters, varistors are needed to weaken the electromagnetic pulse due to the more and more strict computing force requirements. Solid ferrite bead filters can protect some electronic components that are very sensitive to noise. This filter is cheaper than an LC filter and can be triggered at any time.[68, 110]

Manufacturer	Frequency Range, MHz
Fire-Rite Products Corp.	0.2–1000
Ferrishield	30–2450
Ferroxcube	0.2–200
Kitagawa Inc.	0.15–100
Murata	Miniature, for PCB installation
NEC/Tokin	0.1–300
Parker Chomerics	30–200
Laird	30–2,000
TDK	10–500
Leader Tech, Inc	1–2,450
Wurth Elektronik	1–1,000 And also miniature, for PCB installation
Emicore Corp.	0.1–1,00

Figure 2.12: Response frequencies of ferrite based filters produced by different

2.6 The resilience of the Power Grid to nuclear EMP

Because of the power grid's involvement in every aspect of modern life, a breakdown of the power system would bring a country's ordinary life to a complete standstill and even chaos. The attack mode makes them have a vast range of nuclear weapons, in the process of launch and movement are difficult to block completely. Some weapons carry warheads separate will be more challenging to make fall against nuclear missiles complete protection, the nuclear electromagnetic pulse has an extensive range at the same time. These weapons make a nuclear attack if the grid is deliberately corresponding to prepare and almost impossible to be comprehensive effectively. Electromagnetic pulse attacks for power equipment and electronic equipment are devastating and because the transmission line equipment in the power system essential relies on electronic control equipment. Suppose the power system staff wants to protect the power transformer equipment. In that case, it must be conducted under the condition of the electronic equipment guarantee to ensure the protection of power grids has the largest maneuverability. This thesis presents the power system resilience strategy under the need for the power system's electronic equipment to work typically. Because maintenance and replacement of electrical equipment takes a long time and is economically costly, the duration of a nuclear EMP is not days, as in a severe natural disaster, but minutes. So the power grid's resilience strategy to nuclear EMP would be to preserve power rather than maintain control.

Chapter 3: The Nuclear EMP Strike On The Power Transformer

3.1 Introduction

In the analysis of the three stages of a nuclear EMP strike in Chapter 2, it has been shown that the E3 wave has the most significant impact on electrical equipment such as power transformers. Therefore the power equipment in the E3 wave will be simulated to explore its influence on the power equipment. This thesis focuses on power transformers research based on previous research and simulation of cable and transmission towers. Electromagnetic simulation software CST Studio will analyze the effects of standard dry-type transformers on the equipment in E3 waves. After that, the MATLAB Simulink module is used for fault simulation to observe the power transformer's fault form.

3.2 Nuclear EMP simulation in transformer

Before conducting the electromagnetic simulation, the simulation object's material should be selected first because different materials have different electrical and magnetic conductivity. According to the following formula:

$$B = \mu H$$

B is magnetic flux density, H is magnetic field strength, μ is the magnetic conductivity. Because the magnetic flux density in the ferromagnetic material used by the iron core changes non-linearly, the magnetic hysteresis phenomenon will appear in the iron core when the strength rises to a certain intensity. When the transformer core is in a saturation state, the core's magnetic flux density and magnetic field strength will no longer have a linear relationship with the magnetic field strength. So, when the core is saturated or oversaturated, harmonic current will be generated in the transformer's primary and secondary sides. Therefore, electromagnetic simulation with appropriate materials is helpful to determine the operating state of the core.

Simultaneously, because the E3 wave in the nuclear EMP that has the most significant impact on the electrical equipment is the distortion of the geomagnetic field caused by the moving weapon debris and the ionized atmosphere's movement, the transformer elements will generate a large induced current. This inductive current may cause an overload of power transmission lines and transformers.[12, 69, 125] The electrical conductivity needs to be used to calculate these induced currents.

Component of transformer	**Material**
Coil	copper
Iron core	iron
Terminal blocks	copper
Isulating pad/board/column	epoxy resin
Support channel	steel-1008
Screw and nut	steel-1008
Rectifier board	Rogers RO4003C
Rectifier connection bar	aluminum
Rectifier stud	aluminum

Table 3.1: The Component Material Setting Of The Transformer

After setting the transformer material, simulation is carried out through the EMP excitation signal of CST software.

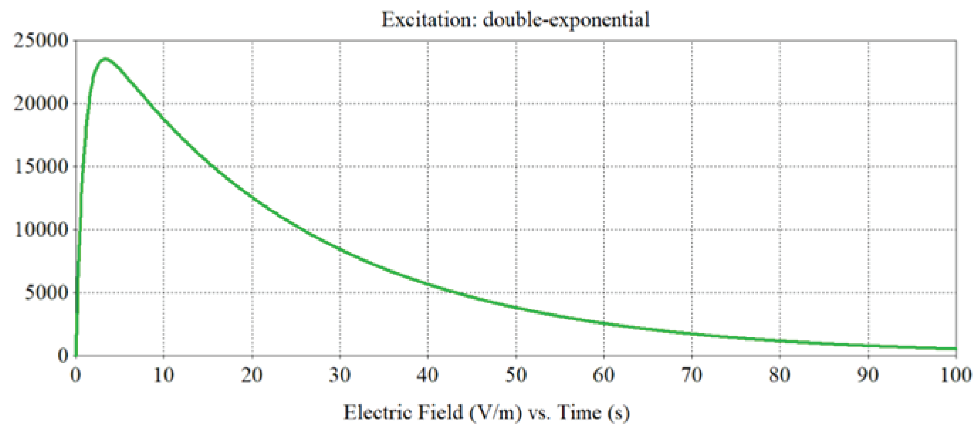


Figure 3.1: The Excitation Signal Of the CST EMP Simulation

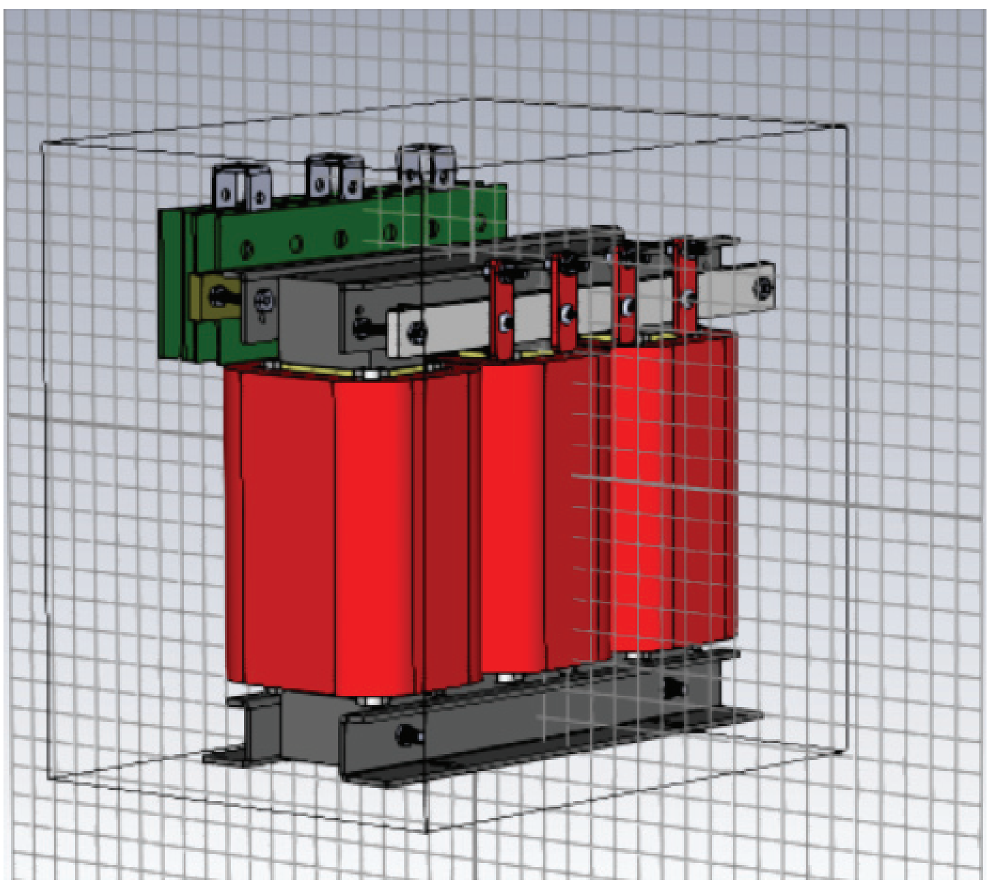


Figure 3.2: Assembly Drawing Of Dry-type Transformer

Let the peak intensity of 24V/km of excitation signal from above the dry type transformer. The magnetic field is perpendicular to the coil winding from top to bottom, and the electric field propagates in the horizontal direction. According to the simulation results, the influence of EMP on the power transformer reaches the maximum when the simulation is carried out to 24 seconds.

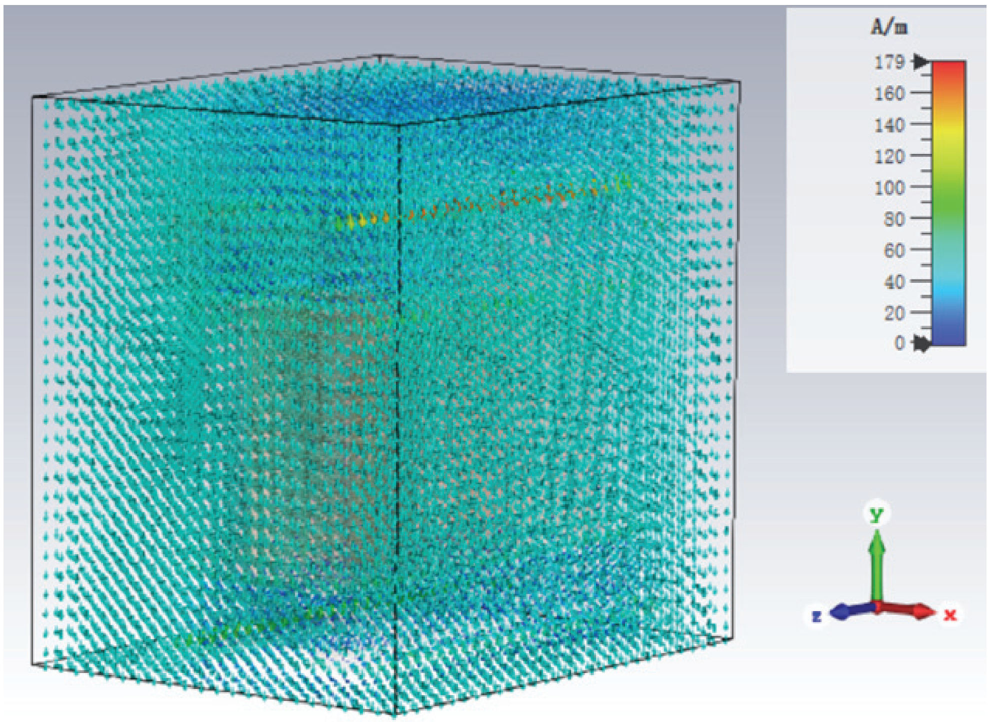


Figure 3.3: Propagation Of Magnetic Field In Dry-type Transformer

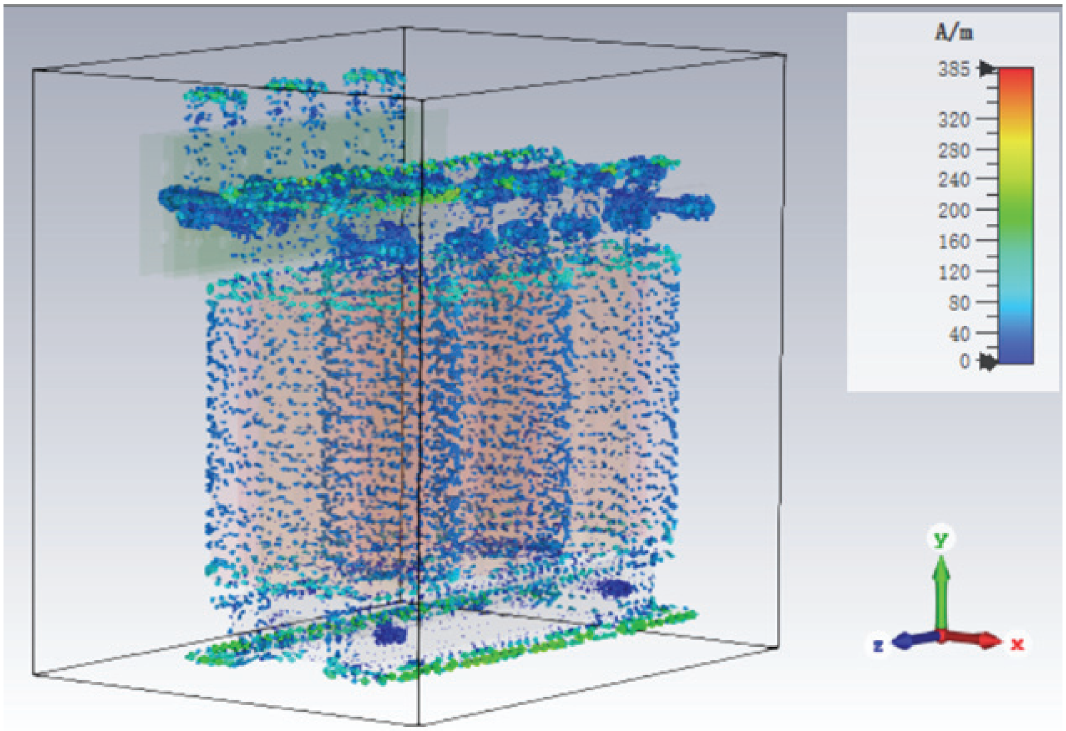


Figure 3.4: Induce Current Of The Dry-type Transformer

As can be seen from figure 3.3 and 3.4, induced current and magnetic field is mainly concentrated on the copper element and iron element, has a sharp edge and at the outside of the transformer is the most significant induced current on the supporting structure. Nevertheless, due to the support structure and the winding and iron core insulation isolation between the two, so will not increase induced current coil and iron core. Next, to further analyze the core and coil state, the two components will be simulated separately.

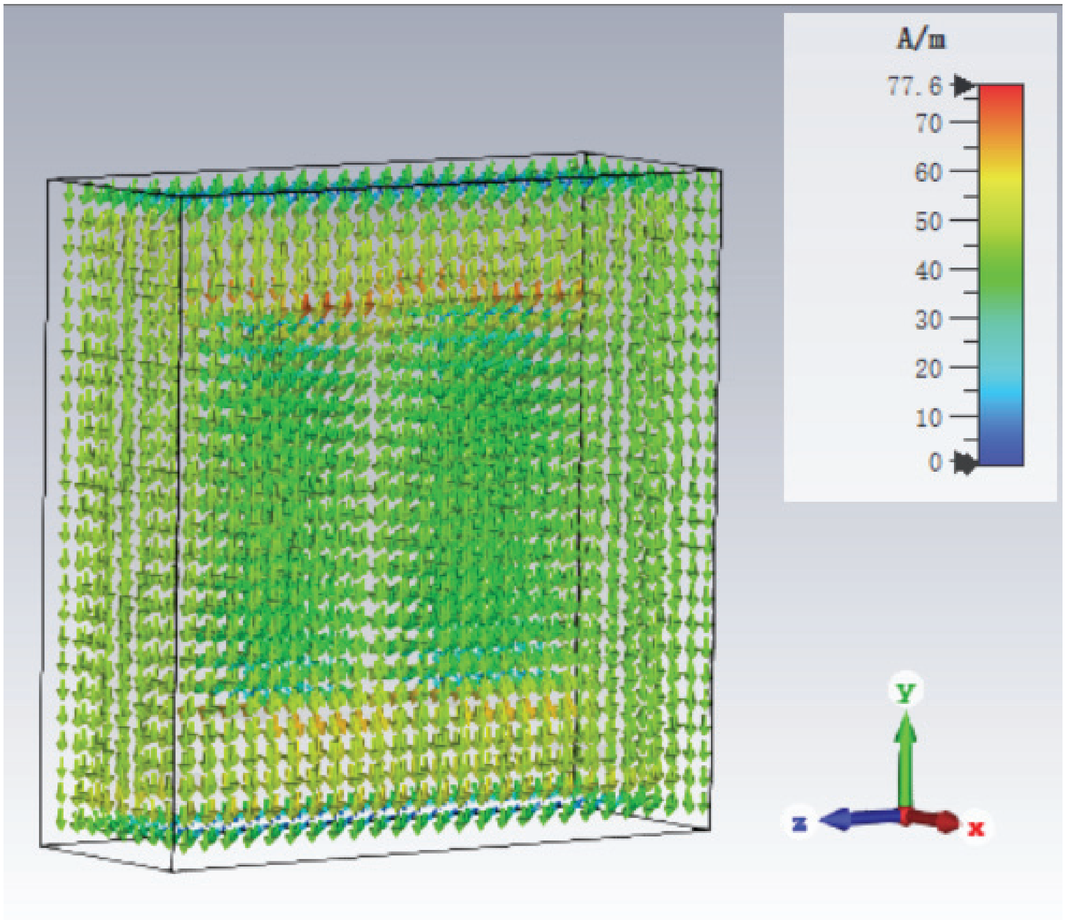


Figure 3.5: Propagation Of Magnetic Field In The Iron Core Of The Dry-type Transformer

In the transformer core's magnetic field propagation results, the transformer core's magnetic field strength is mainly limited to 55 A/m to 60 A/m. According to the core material's soft magnetic characteristics, the magnetic flux density of the transformer under non-working conditions can be obtained.[79, 108] According to the core material's soft magnetic characteristics, the magnetic flux density of the transformer in the non-working state is between 0.87555 T and 0.94155 T.

As the magnetic flux density of the transformer core enters the saturated state at 1.7T, the magnetic flux density brought by the electromagnetic pulse can make the transformer reach the half-saturation and state in the standby state.[13, 58] Due to the economic operation problem, the transformer will at least be in the state close to saturation during the working process. Therefore, when the nuclear EMP hits the transformer in operation, the transformer will quickly reach saturation or even an over-saturation state. At this time, the transformer core will act as the harmonic current source to input harmonic current to the coil, aggravating the coil's possible overcurrent.

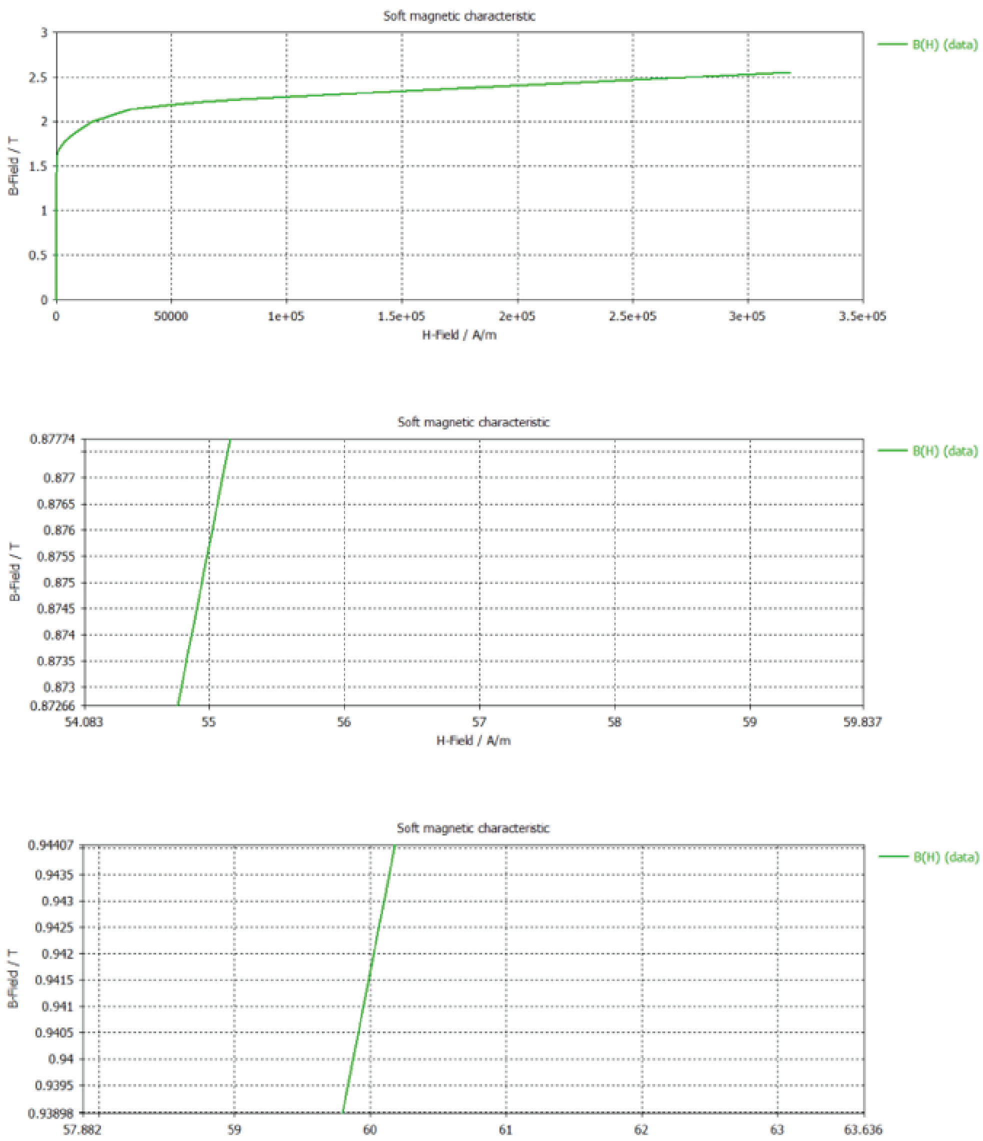


Figure 3.6: Soft Magnetic Characteristic Of the Iron Core

Based on the simulation about induced current on the transformer coil, the induced current on the coil flows following the coil winding direction. Because the frequency of the E3 wave is very small, less than 1Hz, the induced current period becomes very long. However, for the E3 wave with only 10 to 100 seconds, the induced current changes in such a short time are negligible. Therefore, the induced current generated by the E3 wave can be regarded as DC-induced current. Based on the coil's lossy metal impedance curve, the coil surface reactance is very low at the frequency of the E3 wave. Therefore, under the blow of the E3 wave, the coil is prone to high induced current. Chapter 4 will discuss the exact values of the induced current in the operating transformer.

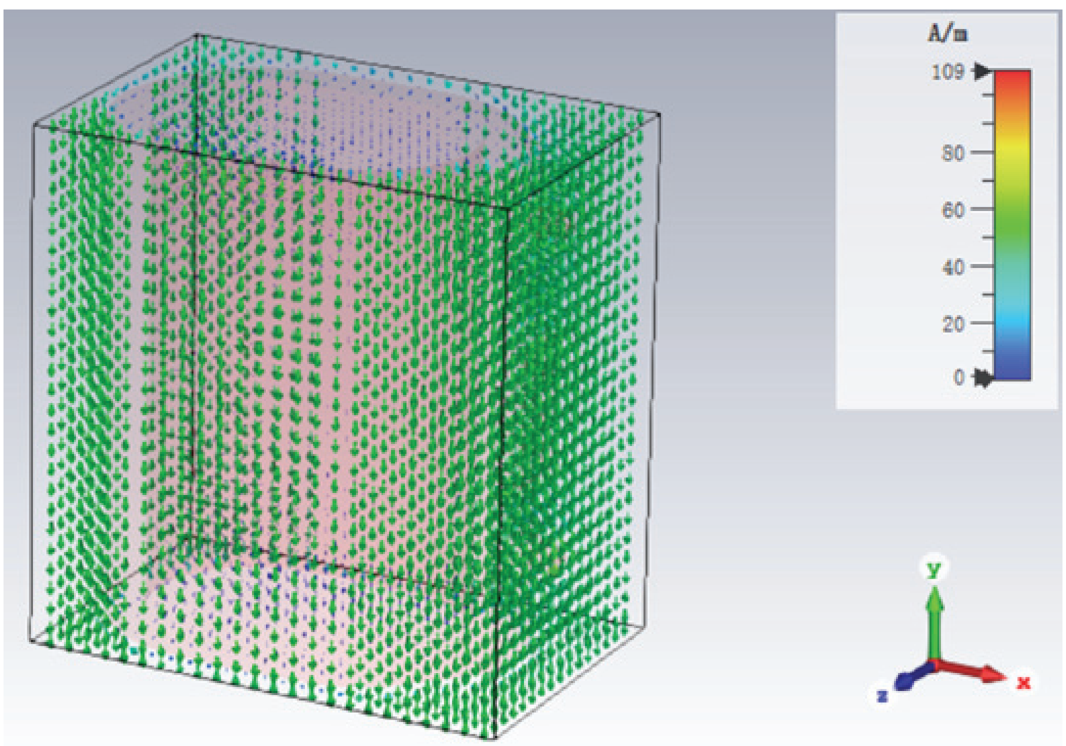


Figure 3.7: Soft Magnetic Characteristic Of the Coil

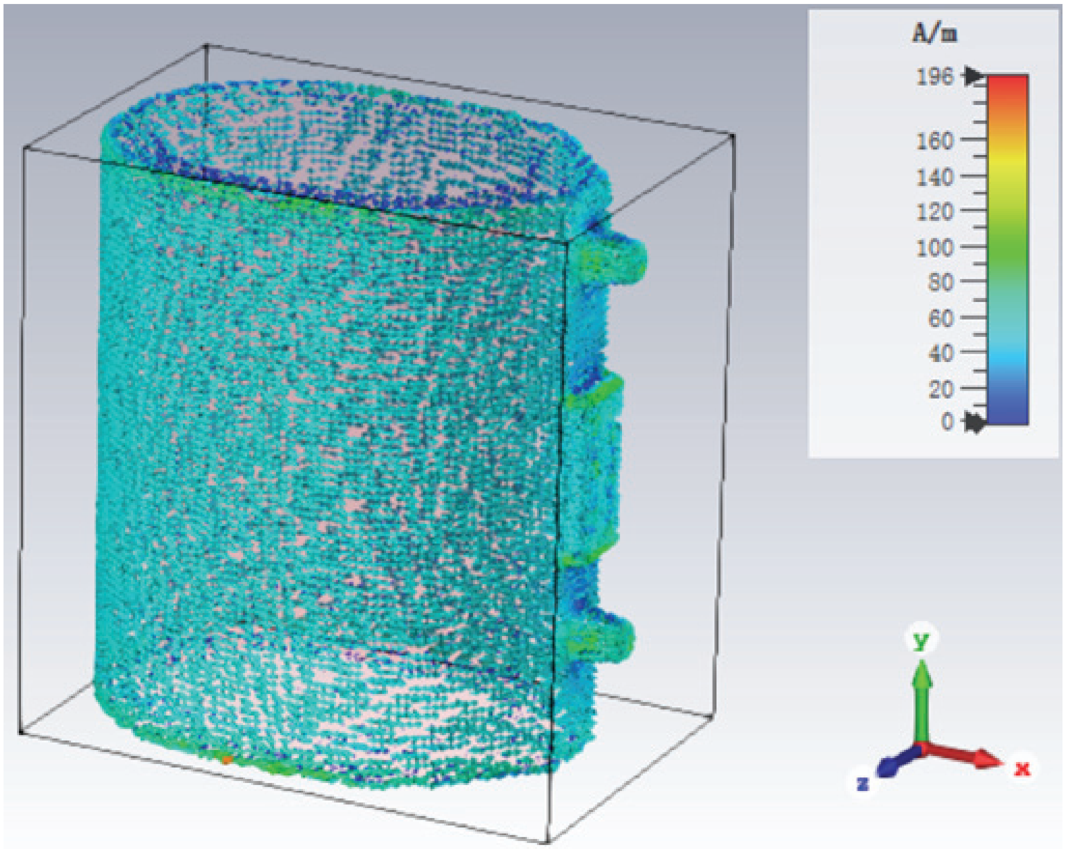


Figure 3.8: Induced Current Of the Coil

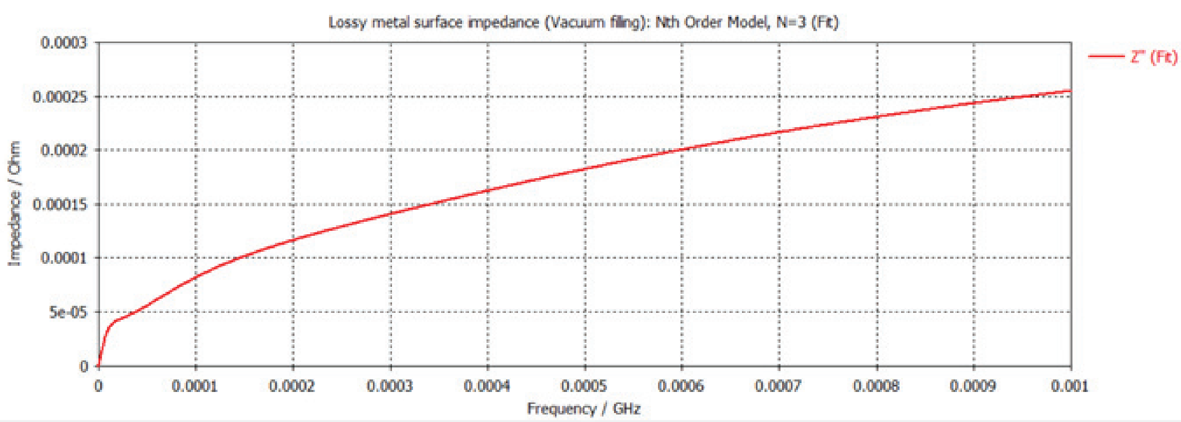


Figure 3.9: Lossy Metal Impedance of the Coil

3.3 Transformer Fault Analysis Based on Simulink

Because the induced current is huge, and the voltage change causes the nature of its generation on the coil caused by the electric field change caused by the magnetic field change, it can be regarded as a kind of inrush current.[67, 82] This inrush current and the harmonic current generated by the saturated iron core is introduced into the power system, which will cause severe current distortion. Based on this characteristic, the model selects the three-phase short circuit inrush fault of the transformer to simulate the induced current accident and uses the saturated transformer to provide harmonics.[32, 80, 122]

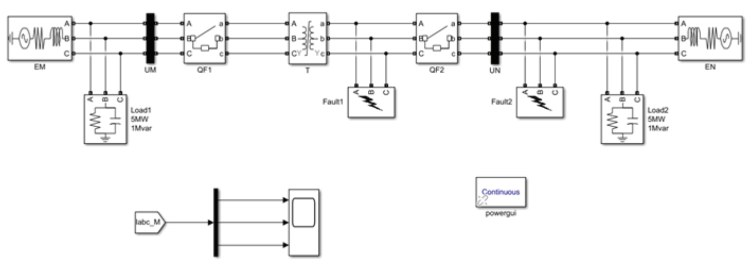


Figure 3.10: Short-circuit inrush current simulation of saturated transformer

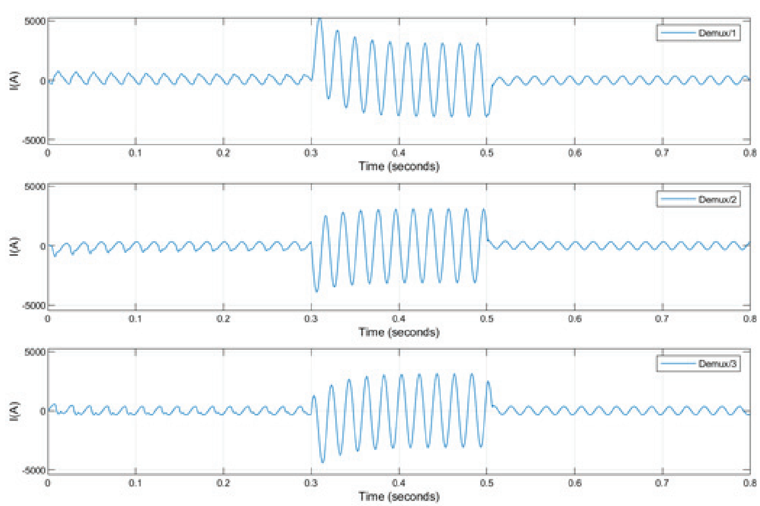


Figure 3.11: Three Phase Fault Current

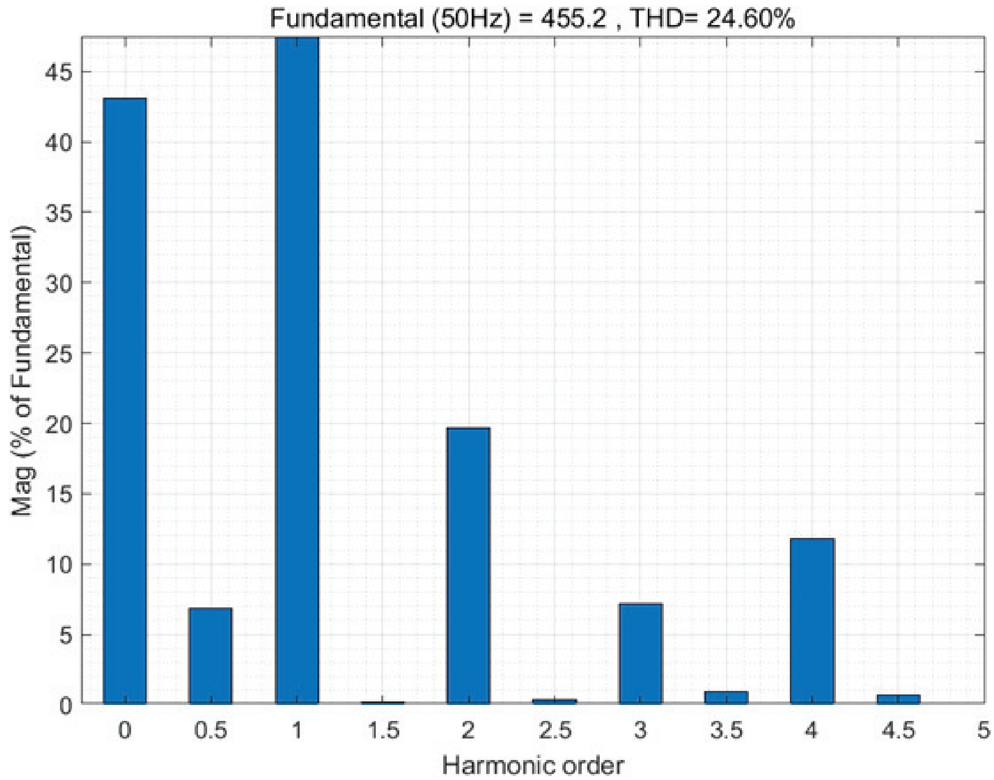


Figure 3.12: Phase Harmonic Ratio

In figure 3.12, the inrush current and harmonic combination, the current in the transmission lines appeared severely distorted. Because the short circuit fault current is different from the induced current of the E3 wave, its frequency is more close to the standard power grid frequency. Therefore, compared with the simulation results, the actual current waveform can match the induced current of the E3 wave in a different direction towards the longitudinal axis's positive direction and negative direction. From Figure.20, in the saturated transformer caused by EMP, the harmonic hazards are mainly concentrated in the second and third harmonics. The amplitude intensity of the second harmonic wave can reach 20.53% of the transmitted wave, the third harmonic wave can reach 8.16% of the transmitted wave, and the third harmonic wave can reach 11.84% of the transmitted wave.

3.4 Conclusion

In this chapter, CST Studio Suite simulates the dry-type transformer and its iron core, coil respectively. The transformer characteristics under the attack of the E3 wave of the nuclear EMP are analyzed through the software's animated contour map. Based on these characteristics, it can be concluded that the transformer will produce harmonic current due to core saturation, accompanied by the high inductive current generated by the coil. Then, according to the analysis results, the transformer's fault simulation is carried out, and the harmonic components of the transformer under the blow of the E3 wave are analyzed by combining the high inrush current brought by the short circuit fault and the saturated core.

Chapter 4: Nuclear EMP Simulation Of IEEE30 Bus System

4.1 Introduction

Chapter3 discusses the main problem of the nuclear EMP attack on the transformer. Although the harmonic components caused by core saturation and supersaturation have been analyzed, it is unclear what harm the inrush current generated by the induced current will cause in the system's transmission. Because the electromagnetic simulation in the third chapter is only for the transformer that is not in operation, it is necessary to carry out EMP simulation to observe the whole system's running state. In this chapter, the GIC module in PowerWorld software will carry out EMP simulation of the IEEE 30 bus system. The EMP source of this chapter is the time-varying series voltage input. The simulation can provide the induced current, reactive power loss, EMP electric field intensity, and line load. The power system's problems under operation conditions can be shown when it is hit and provide a reference for the resilience strategy through these data.[120]

4.2 30 Bus System Simulation

Set the normalized electric field of the E3 wave as 24 V/km, which is the same as the CST studio's excitation signal. Because the nuclear electromagnetic pulse is diffused outward from the explosion center's point, the electrical system facilities' position relative to the center of the explosion is crucial. It is necessary to set the longitude and latitude of the explosion center and the bus and calculate the attack situation suffered by each part of the system. In this simulation, since IEEE does not set the bus coordinates, each bus's coordinates can only be estimated roughly according to its name and the length of transmission lines between the buses. Then use the Power World's time function to calculate the time-varying electric field strength to each substation as the simulation's excitation signal.[41, 88, 109]

Bus Number	Bus Name	Latitude	Longitude
1	Glen Lyn1	31	-94
2	Claytor2	31	-94.5
3	Kumis3	31	-92
4	Hancock4	30.5	-92.1
5	Fieldale5	30	-92.5
6	Roanoke6	31.5	-91
7	Blaine7	30.5	-92.5
8	Reusens8	32	-90
9	Roanoke9	31.5	-91
10	Roanoke10	31.5	-91
11	Roanoke11	31.5	-91
12	Hancock12	30.5	-92.1
13	Hancock13	30.5	-92.1
14	Bus 14	30.5	-94
15	Bus 15	31	-94
16	Bus 16	31	-91.5
17	Bus 17	31.5	-91
18	Bus 18	31	-93.5
19	Bus 19	31	-91.5
20	Bus 20	32	-90.5
21	Bus 21	32	-92.5
22	Bus 22	32	-92
23	Bus 23	31	-93
24	Bus 24	31	-92
25	Bus 25	33	-90
26	Bus 26	33	-90
27	Cloverdl27	35	-90
28	Cloverdl28	35	-90
29	Bus 29	31	-92
30	Bus 30	33	-91
Center	Center	31.5	-91

Table 4.1: The Coordinates Of The Explosion Center And Each Bus

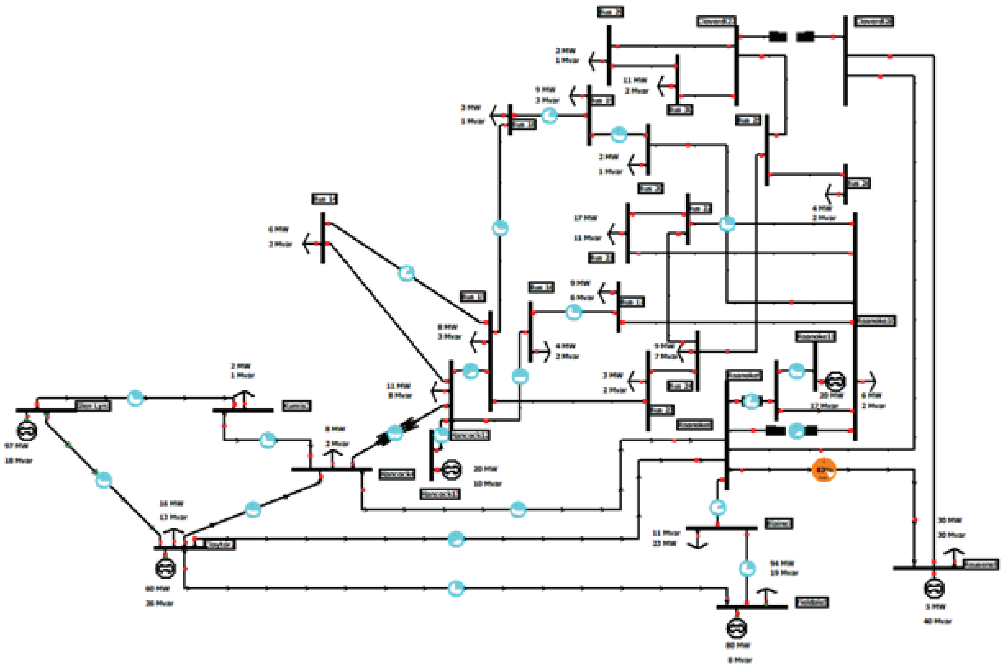


Figure 4.1: The IEEE 30 Bus System

It can be seen from Table 4.1 and Figure 4.1 that the central point of the simulated explosion is in the center of the whole system. After the setting, the transformer's EMP-induced current in the system and the system's reactive power loss data can be obtained. The buses' electric field intensity curve shows two higher pulses in the E3 wave of the electromagnetic pulse. However, in figure 4.2, the EMP-induced current curve of the transformer that the first pulse has the most significant impact on the power grid. By comparing the reactive power loss between transformers and substations, it can be seen that the reactive power loss of the power system in EMP shock almost all comes from transformers. Impingement caused by high inductive current and reactive power loss of the transformer is the main problem of EMP to the power grid.

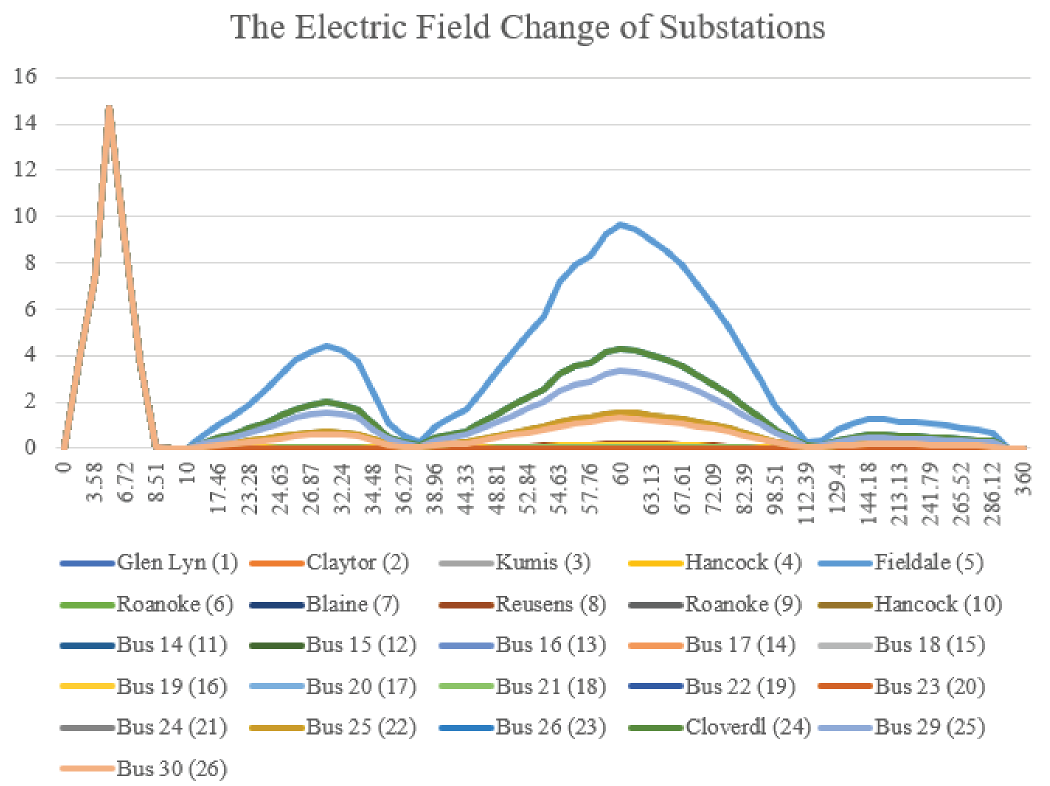


Figure 4.2: The Electric Field Change of Substations

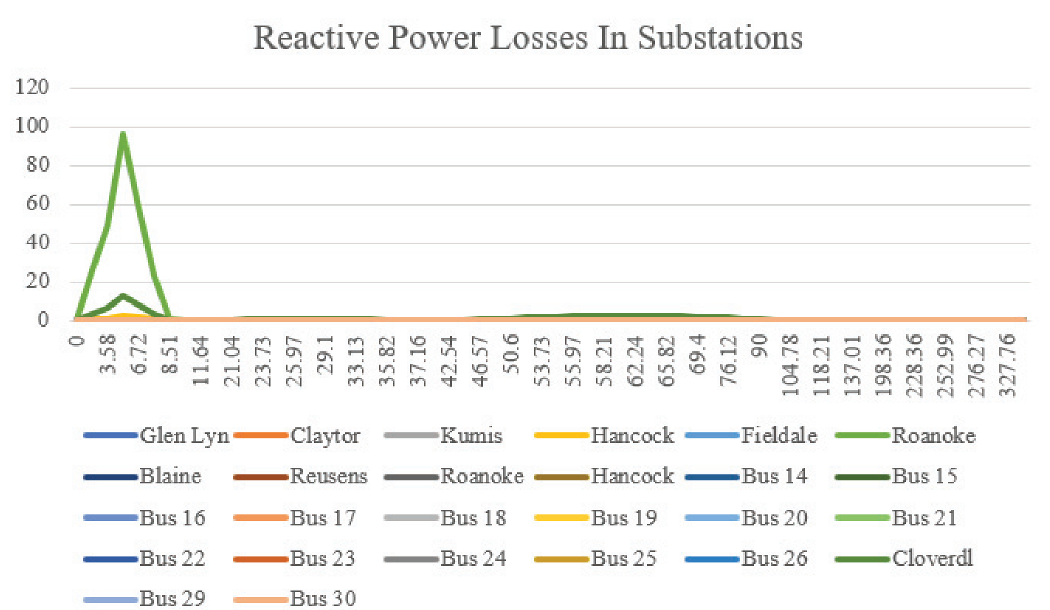


Figure 4.3: Reactive Power Losses In Substations

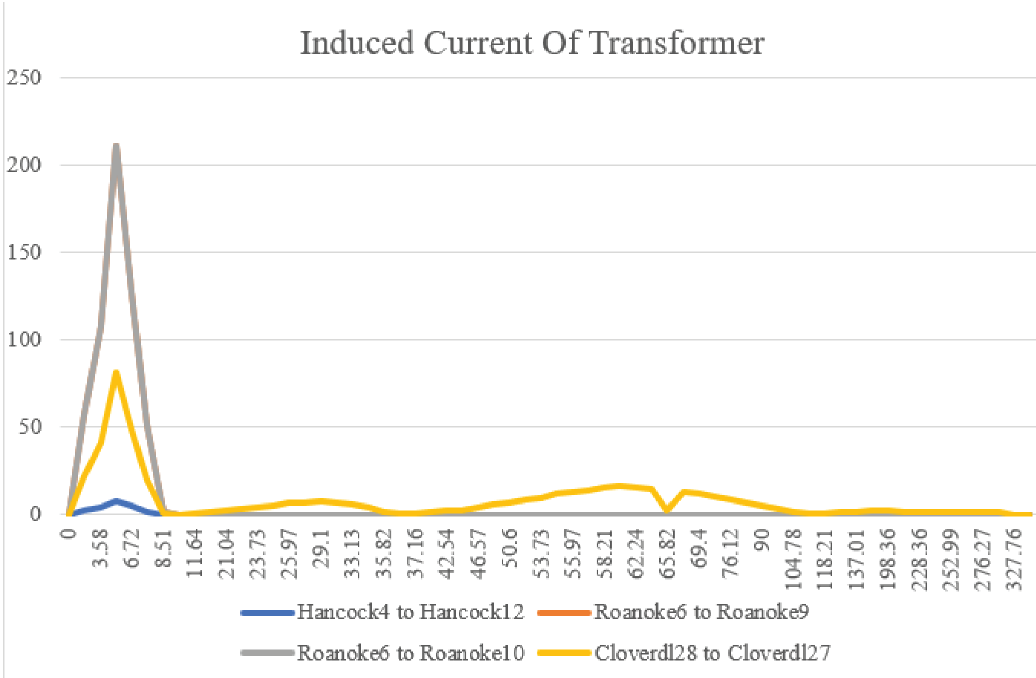


Figure 4.4: Induced Current Of Transformer

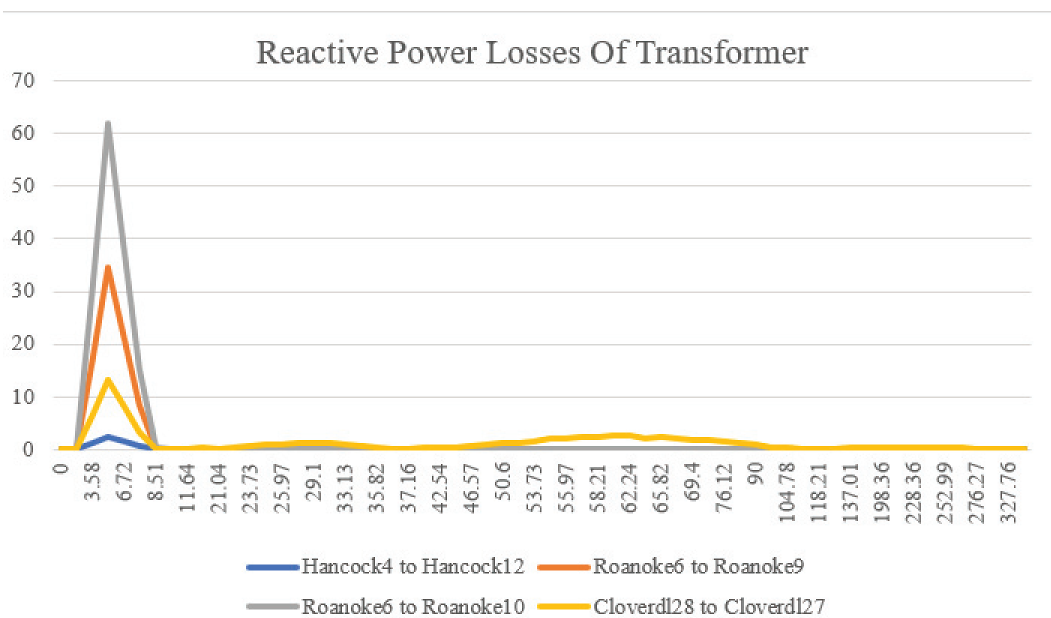


Figure 4.5: Reactive Power Losses Of Transformer

Another problem with severe implications for grid security is that an EMP attack on the grid can overload transformers and transmission lines.

In Figure 4.6, the transformer between bus 6 and 10 and the transmission line between bus 6 and 8 are close to full load. As the EMP lasts for 5.37 seconds, the pulse reaches its peak, at which time the transformer load of bus 6 and 10 has reached 180%. In this system, the power side active power is 283.98 MW and the reactive power is 204.23 Mvar, and the load side active power is 277.4 MW, and the reactive power is 126.9 Mvar. The system is close to saturation, but there is still room for reactive power adjustment, and the explosion center is close enough to the system. Therefore, for this system, there will be no more severe line load than this incident.

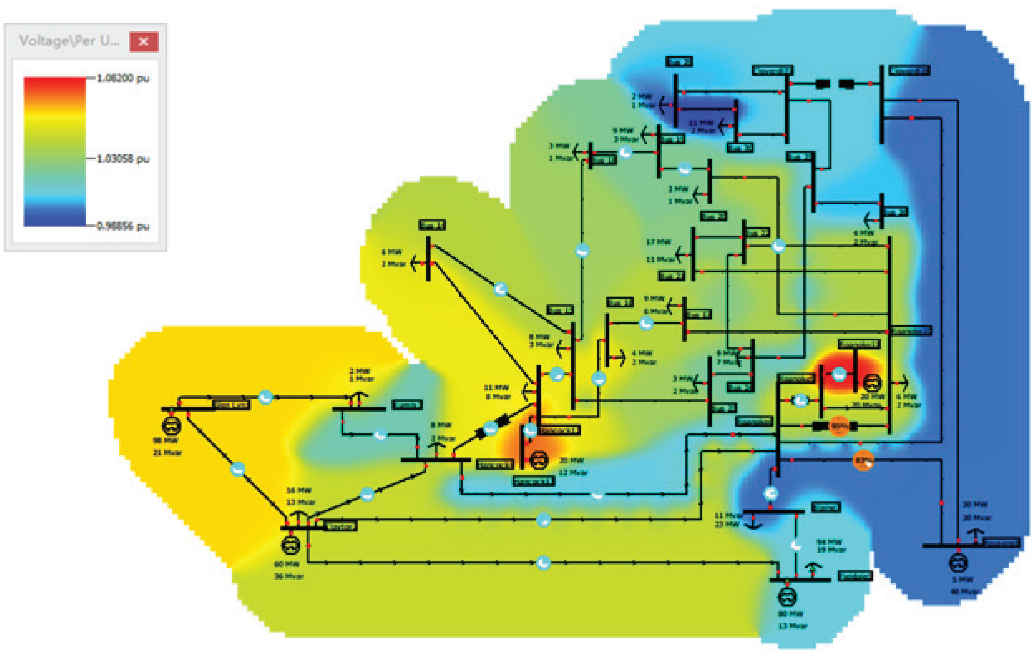


Figure 4.6: The Contouring Picture Of The Voltage Per Unit Magnitude In 3.53 second during the EMP Attack

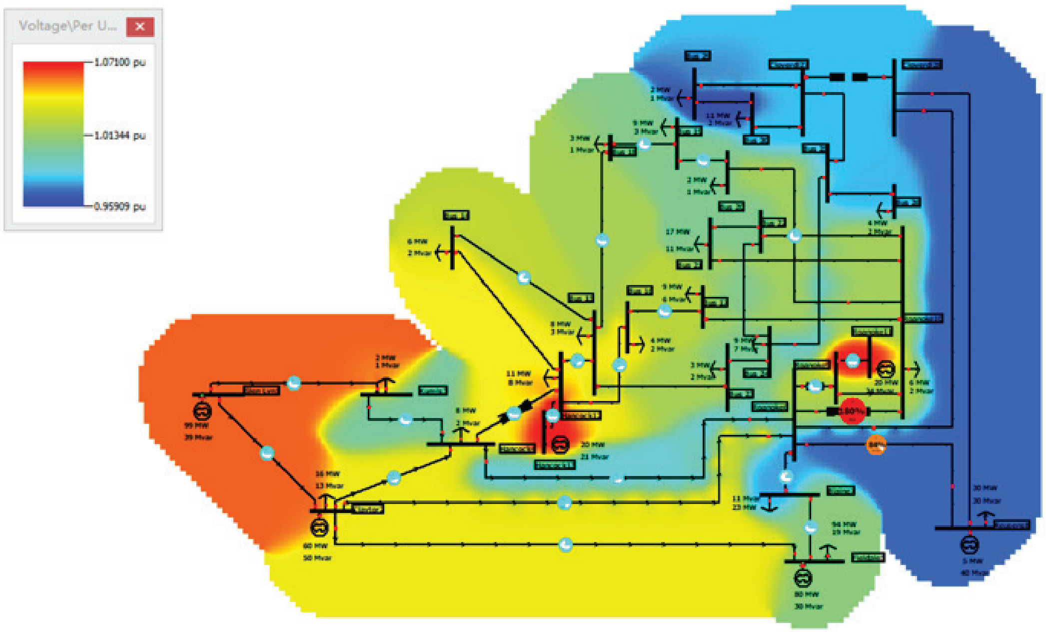


Figure 4.7: The Contouring Picture Of The Voltage Per Unit Magnitude In 5.37 second during the EMP Attack

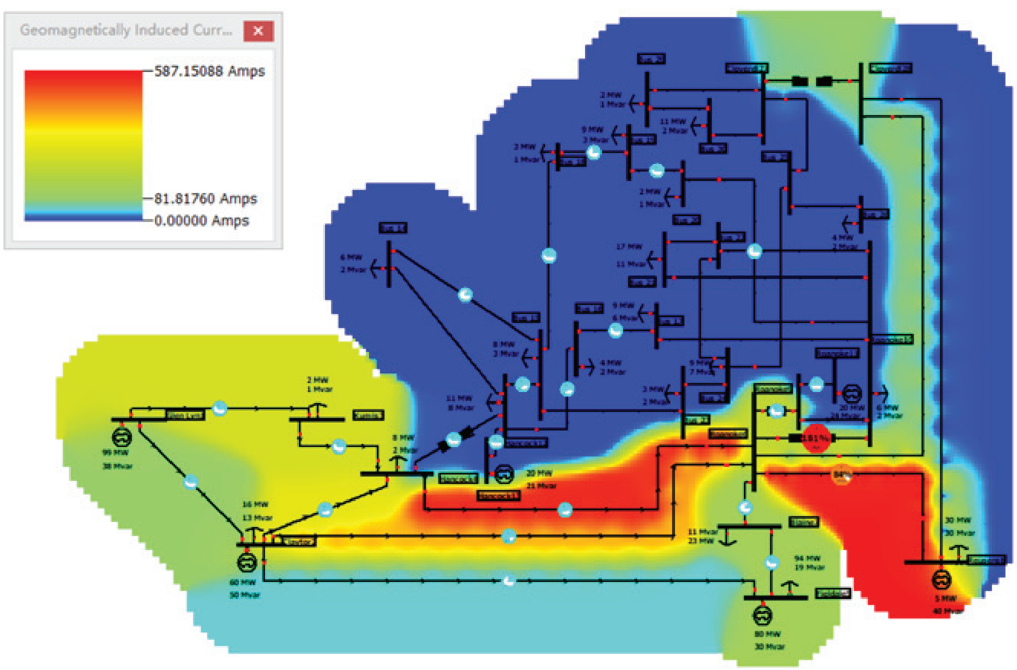


Figure 4.8: The Contouring Picture Of The Geomagnetic Induced Current In 5.37 second during the EMP Attack

Tables and Results

Areas | Buses | Generators | DC Lines | Lines | Line Shunts | Loads | Switched Shunts | Substations | Transformers | System Summary | G-Matrix | Multi-Terminal DC Lines | VSC DC Lines

	Bus Num Hi ▲	Bus Name High	Bus Num Med	Bus Name Med	Bus Num Ter	Bus Name Ter	Circuit	Transformer Per Phase Effective GIC, Amps	GIC Mvar Losses	Transformer Per Unit Effective GIC	Neutral Current (Amps)
1	4	Hancock4	12	Hancock12	0		1	7.925	2.27	0.013	23.776
2	6	Roanoke6	9	Roanoke9	0		1	211.216	33.09	0.341	-633.648
3	6	Roanoke6	10	Roanoke10	0		1	211.216	59.44	0.341	-633.648
4	28	Cloverdl28	27	Cloverdl27	0		1	81.275	12.62	0.131	-243.825

Figure 4.9: The EMP Simulation Result Of Transformer

In the EMP simulation, the induced current goes through a pulse with a maximum of 211.216 Amps between 0 second and 8.51 second. Simultaneously, the transformer located in the middle of Bus 6 and 10 will also bear the induced current in the transmission lines at both ends. Because the transmission line between Bus 4 and 6 has a peak value of 560.19 amperes of induced current from 6 bus to the transformer between Bus 6 and 10, the transformer has a severe overload. For the transmission line from bus 6 to Bus 8, the load on the line is very high due to the massive difference between the power plant's generating power located on Bus 8 and the load power demand on Bus 8 and the peak induced current 586.67 Amps. Compared with the fault current caused by a short circuit fault, the induced current in EMP simulation is much smaller. However, it is still necessary to consider all kinds of faults in an overload state, such as transformer overheating and arc.

4.3 Conclusion

In this chapter, we use PowerWorld software to simulate the IEEE 30 bus system. The simulation electric field variation can correspond to the two pulses of the E3 waveform in the previous thesis. Still, it is the first set of pulses with a more substantial amplitude that significantly impacts the power system. Most of the significant problems caused by the E3 wave are transformers. First of all, the transformer will cause reactive power loss after being hit by EMP, and it changes with the change of pulse. The decrease of reactive power will make part of the voltage drop in the power system. This process takes place in a brief period and will cause short-term voltage shock. The electromagnetic pulse also generates a high amount of induced current in the transformer and transmission line, which poses a risk of overload in the transformer and transmission line. Overloaded transformers and transmission lines may be damaged due to overheating. Therefore, the protection and control methods for this fault will be discussed in the next chapter.

Chapter 5: Resilience Strategy Of Power Grid Against EMP

5.1 Introduction

Chapters 3 and 4 show the problems of power grids and transformers under EMP strikes. When the grid experiences an EMP blow, transmission lines or transformers may experience overload and reactive power loss and fluctuation due to a short voltage drop in some systems. The power grid overload is mainly due to the high induction current in the power transformer, transmission line, and regular operation. The current in the process of superposition and the primary source of reactive power losses is the transformer. So in this chapter, the transformer in the discussion process seeks solutions and summarizes the power system's resilience to cope with an EMP attack tactics.

5.2 Harmonic Processing Of Saturated And Supersaturated Transformers

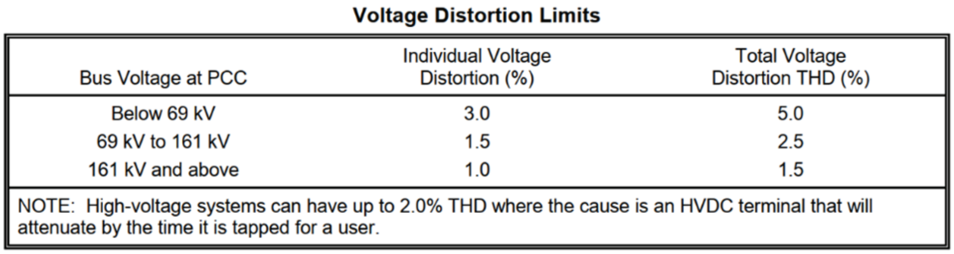
The non-linear relationship between the flux density and the transformer core's magnetic field strength mainly causes harmonic in the transformer. When the transformer core tends to saturation, the flux density no longer increases with the increase of the magnetic field strength, and the permeability decreases.[2, 18, 18, 89, 106] According to the core's soft magnetic characteristic curve, when the transformer core is unsaturated, the magnetic field intensity H has a linear relationship with the magnetic flux density B. At this point, the transformer's magnetic field intensity is sine current applied at both ends of the transformer. The magnetic field intensity in the transformer is proportional to the current in the coil. Hence, both the magnetic flux density and magnetic field intensity are sine waves with the same system frequency.[10, 41, 97] The relationship between the magnetic flux density and the electric magnetic strength is nonlinear when the transformer's core is saturated.

$$\Phi_m = BA$$

$$E = 4.44 f N \Phi_m$$

$$I_m = \frac{E}{Z_m}$$

A is the area of core cross-sectional, E is the induced electromotive force generated by the magnetic field in the coil of the transformer, f is the frequency of the power grid, N is the number of the coil turns of the transformer, Phi_m is the coil flux, I_m is the exciting current in the coil, Z_m is the exciting reactance of the transformer. When the magnetic flux density is nonlinear growth, the transformer's magnetic flux density will not change according to the power system's current changes. The excitation current generated by it will also distort and produce harmonics. There is no clear standard for the transformer's harmonic ratio, so this thesis adopts the suggested harmonic ratio in the ***IEEE Std 519-1992 Harmonic Limits*** as the standard. Suggestions on the acceptable range of harmonics are given:



Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
Below 69 kV	3.0	5.0
69 kV to 161 kV	1.5	2.5
161 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Figure 5.1: IEEE Std 519-1992 Harmonic Limits

According to the operating voltage of the overload transformer bus on both sides of the simulation in Chapter 4, the harmonics limit recommendations are found in Table 5.1 and compared with the harmonics proportion in Figure 3.12, the ratio of harmonics in the saturated transformer has far exceeded the standard in the document. Because excessive harmonics will aggravate the transformer loss, and the heating of the transformer coil and induced current and the induced current will cause serious security risks, it is necessary to adopt appropriate ways to weaken harmonics. Because excessive harmonics will aggravate the transformer loss, and the heating of the transformer coil and induced current and the induced current will cause serious security risks, it is necessary to adopt appropriate ways to weaken harmonics.[70]

First, we filter the second, third, and fourth harmonics of the system, and the following results can be obtained:

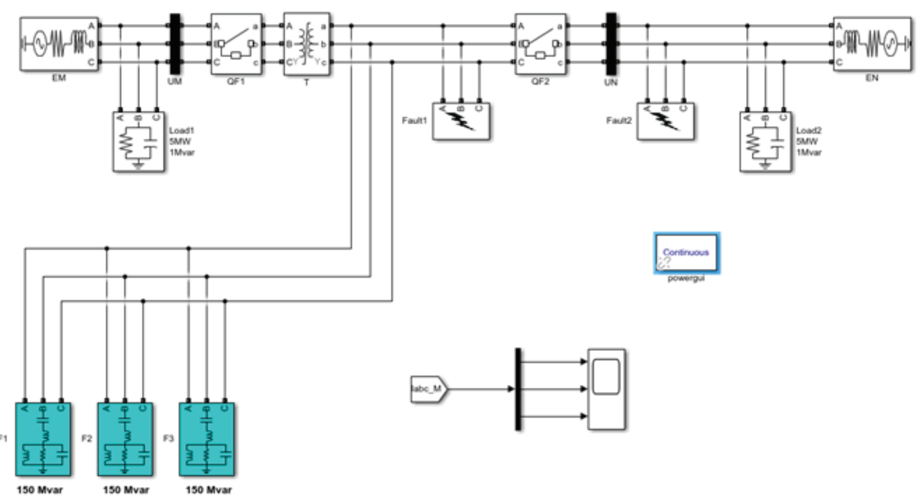


Figure 5.2: The Saturation Transformer Harmonic Simulation Module With Filter

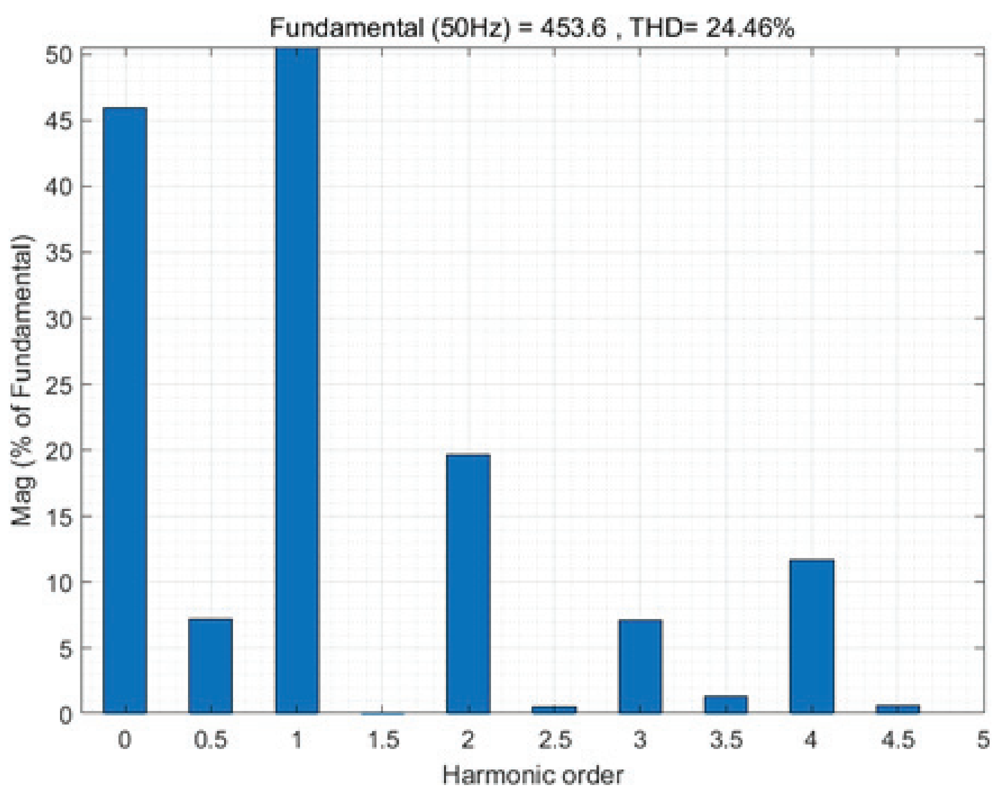


Figure 5.3: The Harmonic Ratio Of Saturation Transformer Simulation Module With Filter

The ratio of the second harmonic decreased from 20.53% to 19.66%, the proportion of the third harmonic decreased from 8.16% to 7.13%, and the proportion of the fourth harmonic decreased from 11.84% to 11.73%. It can be seen from the simulation results that the conventional filter can not effectively reduce the harmonic content of the saturated transformer experiencing inrush current impact. According to the conclusion of chapter 4, in the power system simulation, the transformer causes the system's major reactive power loss. Its characteristic can be regarded as the sudden absorption of reactive power by a high inductor(the transformer's coil). In this case, according to the ampere rule, the electromagnetic field formed with the current through the coil increases the transformer's saturation state.[7, 31, 106, 130] Therefore, a parallel inductor in the line is considered to shunt the inrush current in the transformer.

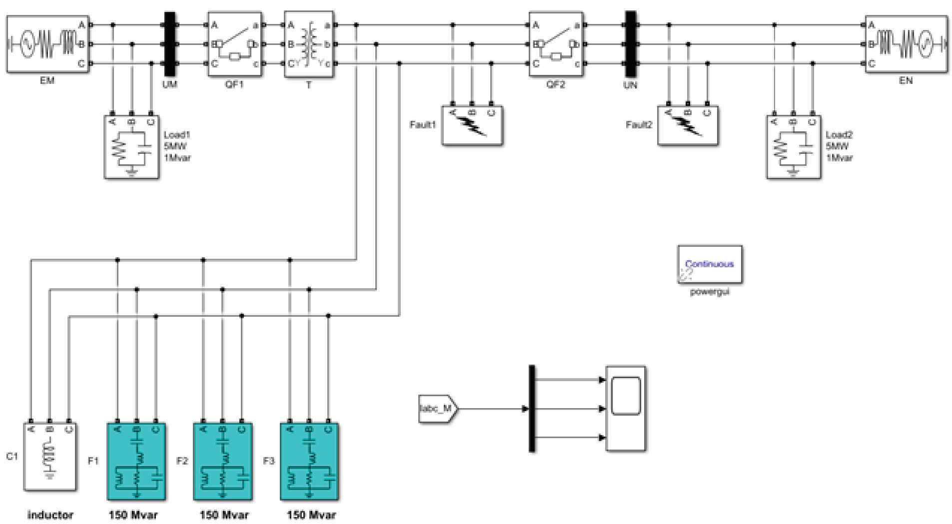


Figure 5.4: The Saturation Transformer Harmonic Simulation Module With Filter And Inductor

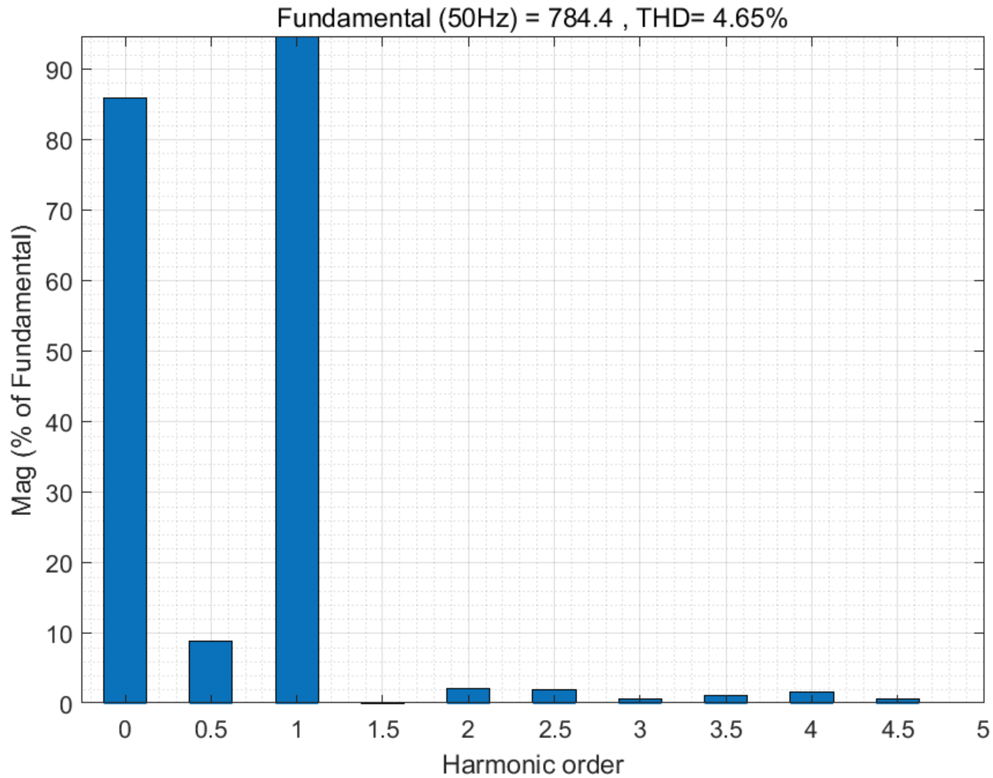


Figure 5.5: The Harmonic Ratio Of Saturation Transformer Simulation Module With Filter And Inductor

In the new system, the proportion of the second harmonic is reduced to 2.24%, the ratio of the third harmonic is reduced to 0.73%, and the fourth harmonic ratio is reduced to 1.71%. The results show that the parallel inductor can effectively reduce the transformer's harmonic current intensity and effectively reduce the transformer's load.

5.3 Resilience Strategy For Transformer Or Line Overload And Reactive Power Losses

In Chapter 4, the simulation of the IEEE30 bus system shows that the transformer in this system mainly bears the impact of the first 8.51 seconds, which is not long, and the subsequently induced current is not large enough to cause damage to the transformer. Assume that the electronic equipment for communication, monitoring, and control of the whole power system is not damaged. Based on the characteristic of the E3 wave impulse, it can be considered to change the power system's power flow through switching regulation to avoid overload of power transformers and transmission lines, thus experiencing the E3 wave attack of EMP in operation state.

As can be seen from Fig. 5.6 and Fig. 5.7, in the whole system, the largest power generation is located in the southwest and Bus 1 generators and a big load connected on Bus 21. The main reason for transformer overload is that most of the power flow generated by the power generation equipment in the south needs to pass through the transformer between Bus 6 and Bus 10 and then transfer from Bus 10 to the north through four branches. The reason for the change of power flow is the power flow from the overloaded transformer into Bus 10 to the north has the shortest transmission line. In parallel with the overloaded transformer, the two transmission paths from Bus 6 through the transformer to Bus 9 and then through the transmission line to Bus 10, and from Bus 4 through the transformer to Bus 12 and then through the transmission line to Bus 15 on the west side still have a significant load allowance. Therefore, the overloaded transformer can be cut off, and two transmission routes with more similar losses can be used for the shunt.[2, 7, 18, 95, 111, 115, 121]

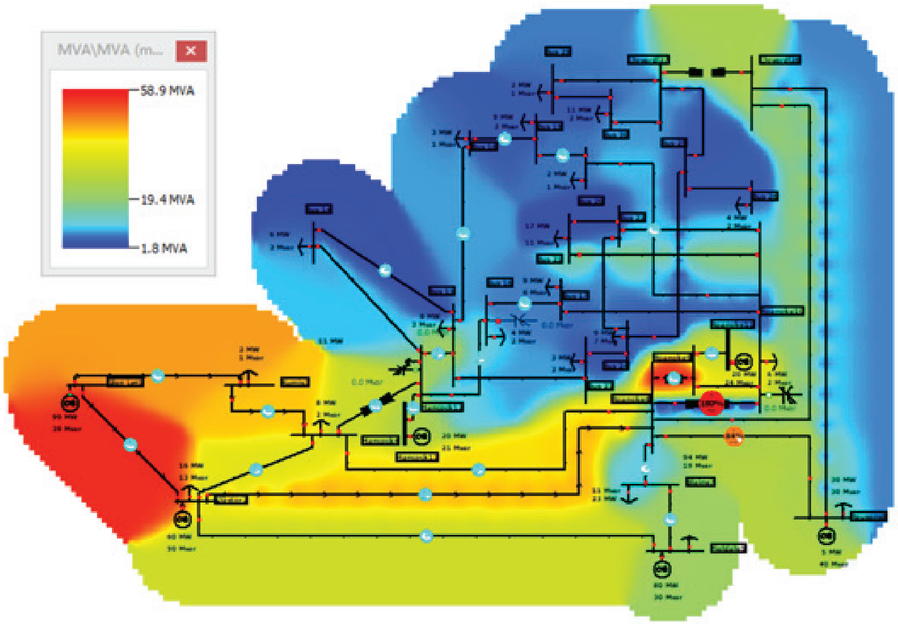


Figure 5.6: Electrical Pulse Simulation Of Transmission Load At 5.37s

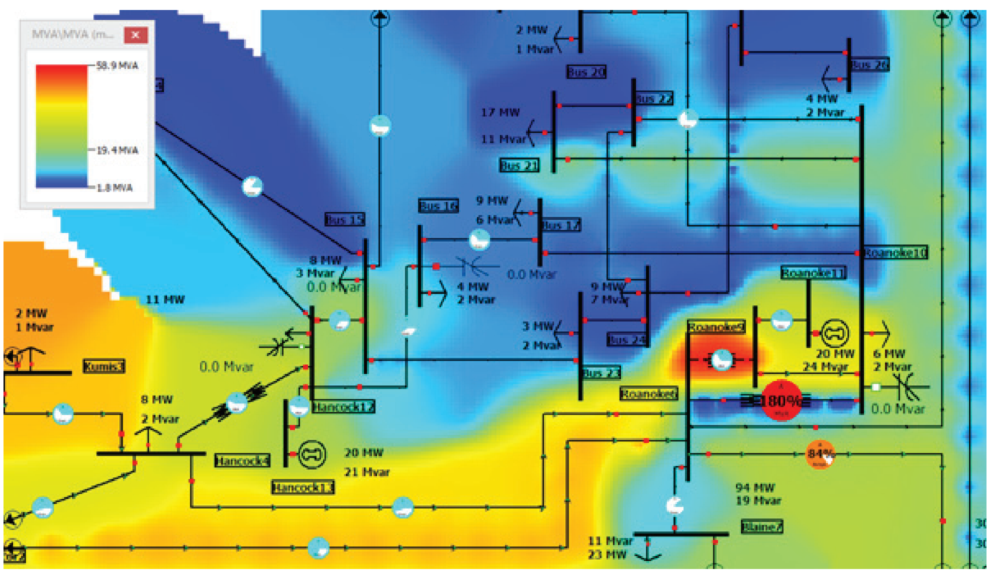


Figure 5.7: Electrical Pulse Simulation Of Local Transmission Load At 5.37s

From Bus	To Bus	Power Flow Resistance (Ohms/Phase)
1	2	3.3454
1	3	7.8756
2	4	9.9317
2	5	8.2241
2	6	10.1233
3	4	2.3
4	6	2.0735
5	7	8.015
6	7	4.6522
6	8	2.0909
6	28	2.9447
8	28	11.0817
9	10	0
9	11	0
10	17	0.3528
10	20	1.0193
10	21	0.379
10	22	0.7917
12	13	0
12	14	1.3406
12	15	0.7209
12	16	1.0291
14	15	2.4067
15	18	1.1685
15	23	1.089
16	17	0.5706
18	19	0.6959
19	20	0.3703
21	22	0.1263
22	24	1.2524
23	24	1.4375
24	25	2.0528
25	26	2.7704
25	27	1.1903
27	29	2.3936
27	30	3.487
29	30	2.6125

Table 5.1: Power Flow Resistance Of Transmission Line

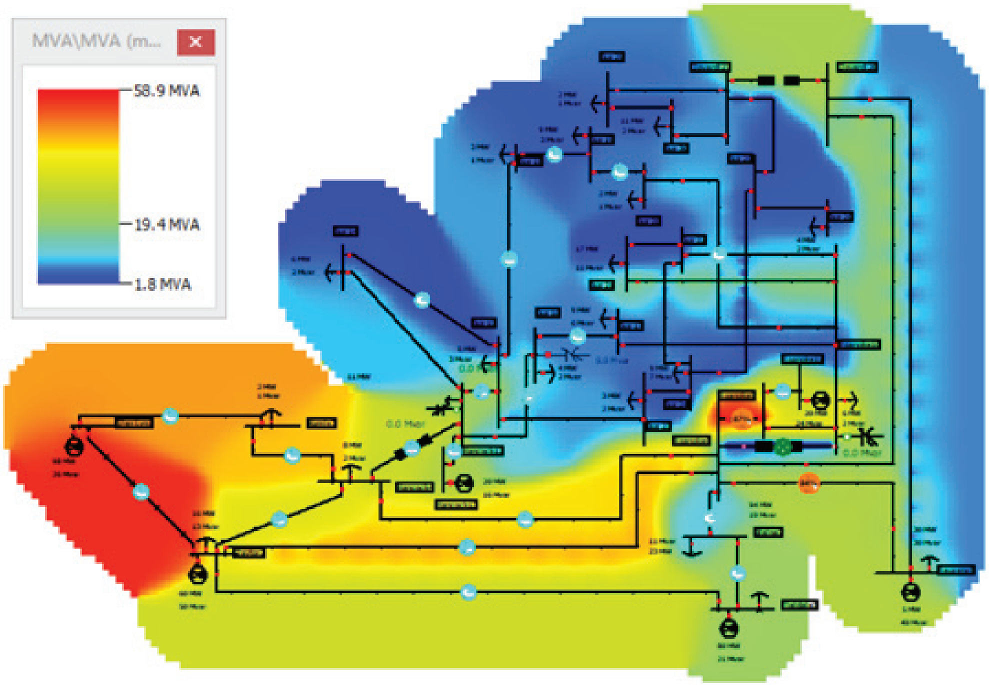


Figure 5.8: Adjusted Electrical Pulse Simulation Of Transmission Load At 5.37s

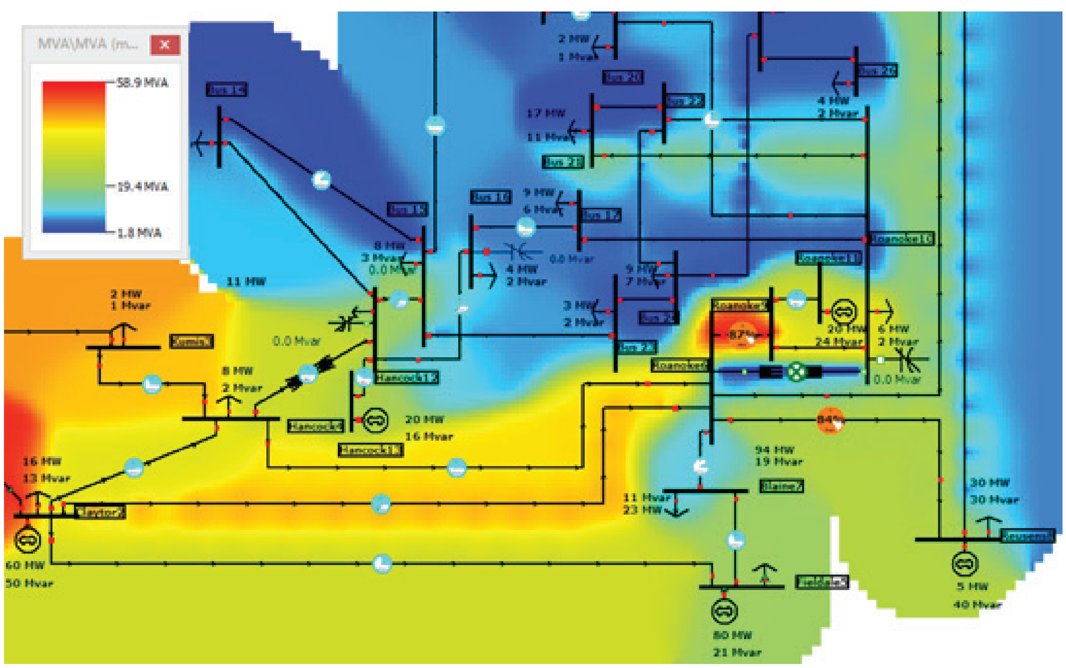


Figure 5.9: Adjusted Electrical Pulse Simulation Of Local Transmission Load At 5.37s

The transformer load between the Bus 4 and Bus 12 increases from 43.2% to 48%, and the load between Bus 6 and Bus 9 increases from 33.5% to 86.8%. At this time, the overload phenomenon is no longer present in the system. However, in the E3 wave simulation of EMP, the electric field and impact reach the maximum at 5.37 second. Therefore, the power system can resist the attack of the E3 wave after adjustment. Simultaneously, the reactive power loss in the system decreased from 107.4 Mvar to 82.2 Mvar due to removing of a transformer.

Based on the previous research, the coaxial cables are very effective against electromagnetic pulses, which results in less load pressure in coaxial cables than in power transformers with GIC.

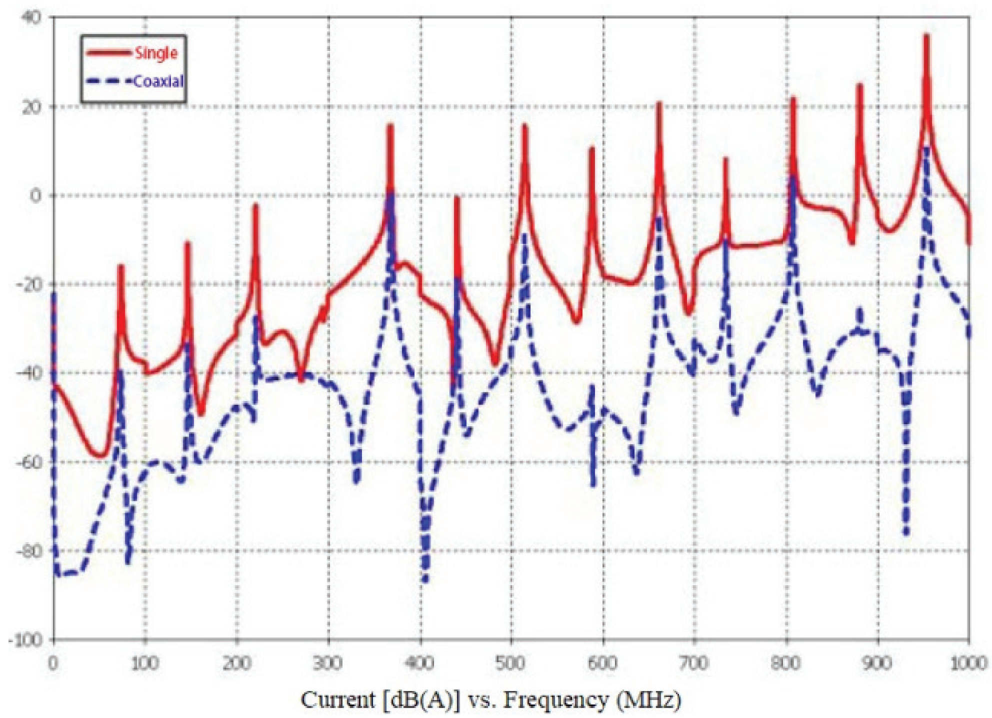


Figure 5.10: Current Induced in Bare Wire and Coaxial Wire

Suppose the control monitoring and communication equipment of the power system fails to cut off the transformer. In that case, In this case, because the transmission line using coaxial cable receives less EMP shock, the overloaded transformer can be shunted to the transmission line by the shunt that has been installed in the power system to alleviate the transformer overload. Switched shunts are used in power systems to inject additional reactive power into the system (capacitive shunts) or absorb excess reactive power (inductive shunts). They may also be used to regulate bus voltage within some specified range. Therefore, in this system, the SVC shunt can be set as capacitive to input reactive power into the power system to compensate the transformer for reactive power.[66, 90, 96, 129]

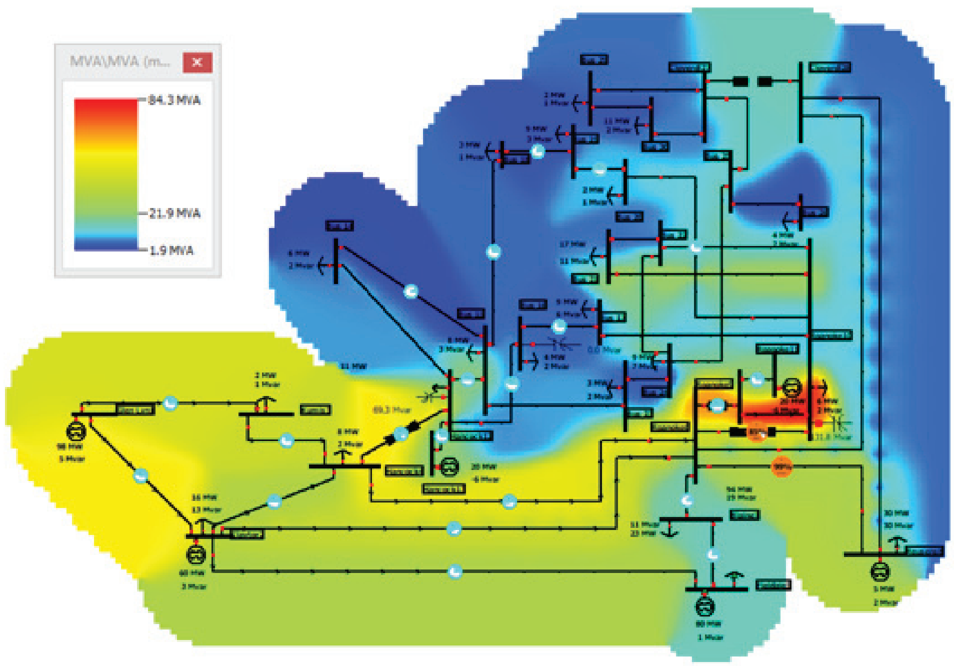


Figure 5.11: Electrical Pulse Simulation Of Local Transmission Load At 5.37s With Shunts

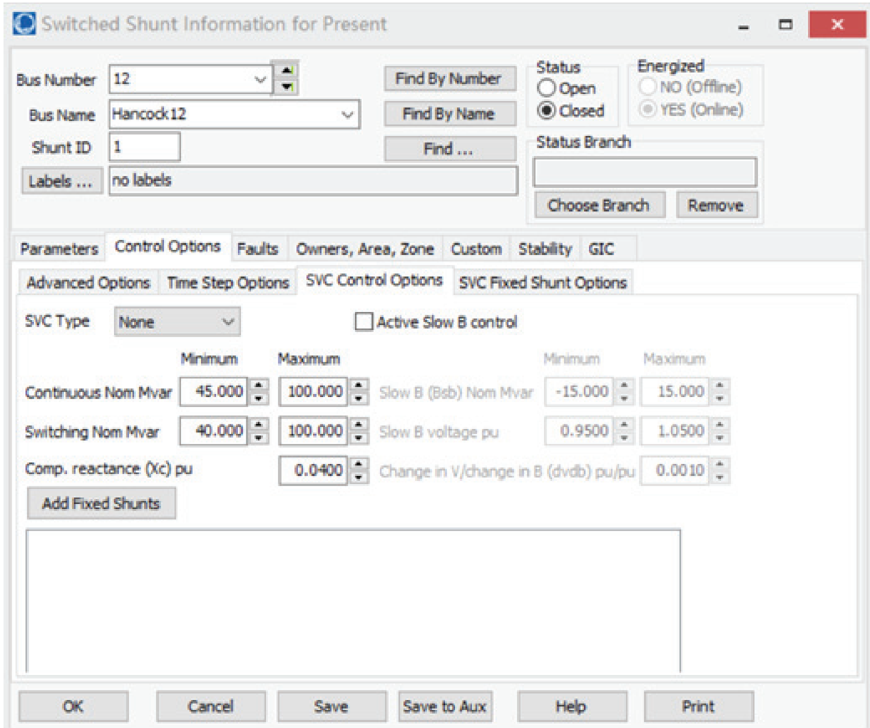


Figure 5.12: Setting Of The SVC Control Switch Shunts in Bus 12

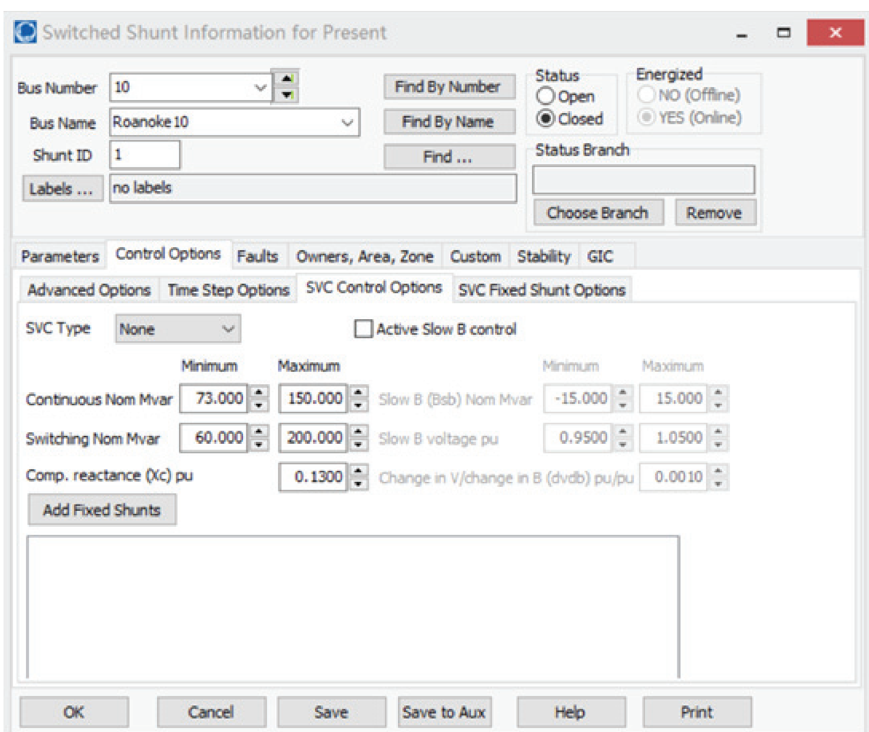


Figure 5.13: Setting Of The SVC Control Switch Shunts in Bus 10

Under the action of the shunt, the transformer load between the rear Bus 4 and Bus 12 increases from 43.2% to 76.1%, the load between Bus 6 and Bus 9 increases from 33.5% to 47.3%, and the transmission line load between Bus 6 to Bus 8 increase from 84% to 98.6%. The reactive power loss in the system decreased from 107.4 Mvar to 101.4 Mvar due to removing a transformer.

It can be known from the above two elastic conclusions to deal with the E3 waveform that the overload of transformer and line can be effectively avoided through reasonable shunt measures by cutting off part of the circuit or parallel SVC shunt on the transformer connection nodes. However, these two methods cannot effectively eliminate the reactive power loss caused by the transformer. The effect of conventional SVC is even worse than that of direct transformer removal. The reason for the reactive power compensation limitation of SVC shunts is that the shunt effect limits the reactive power compensation of the SVC shunt. It should not overload other lines because of the emphasis on reactive power compensation. Therefore, the reactive power loss caused by the transformer can only be compensated by adjusting the power plant's output power.

5.4 Future Protection Trends

In the modern power system, an EMP attack, electronic equipment protection, such as filter SVC in this chapter, is one of the biggest problems. The switch control equipment of the power system is composed of electronic devices. If the power system's design can protect these devices, only in the face of E3 wave hit, or is there a way to protect living this kind of equipment such as power transformer devastating blow. In power transformers, several patents can reduce the possibility of core saturation by adding a non-magnetic gap to the core. Because the induced current of the E3 wave is low-frequency DC, additional shielding induced current winding with low AC resistance and high DC resistance can be arranged in the iron core.

In this thesis, the simulation of the IEEE30 bus system is only carried out under a fixed condition. Since the power system is dynamic stability based on voltage and frequency in the basic operation strategy, the operating power flow in the system will be different from that in this model. The overload problem in the power system will be affected by the variation of the pulse intensity due to the different nuclear EMP burst point locations and the different weapon yields. For example, change the explosion latitude and longitude from (31.5,-91) to (31,-94) in the simulation, the shunts setting cannot solve the overload problem of the power system.

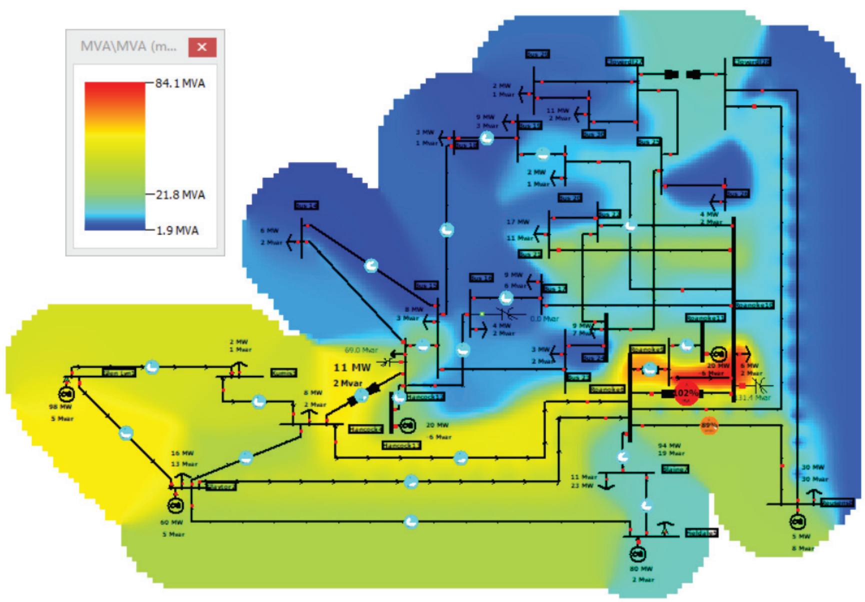


Figure 5.14: Electrical Pulse Simulation Of Local Transmission Load At 5.37s with old Shunts and explosion center (31,-94)

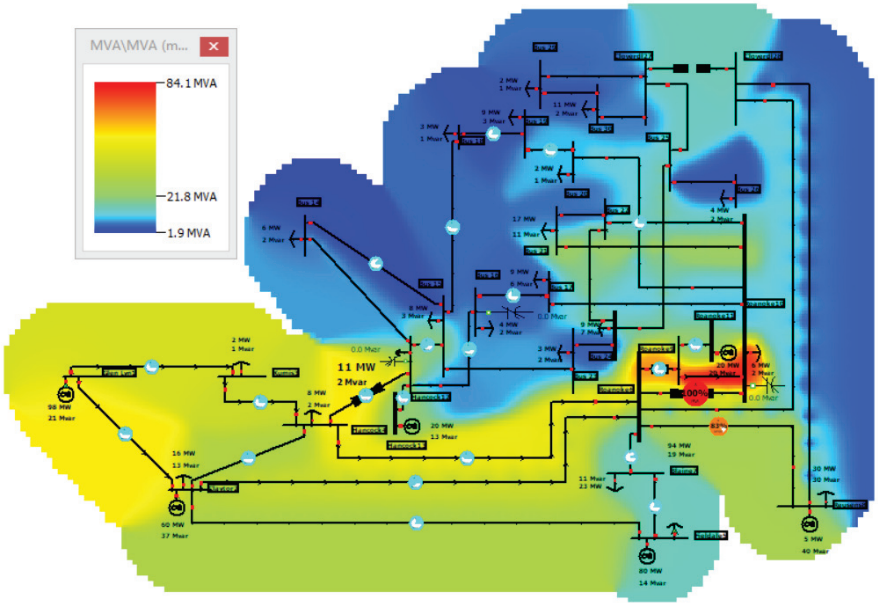


Figure 5.15: Electrical Pulse Simulation Of Local Transmission Load At 3.59s no shunts with explosion center

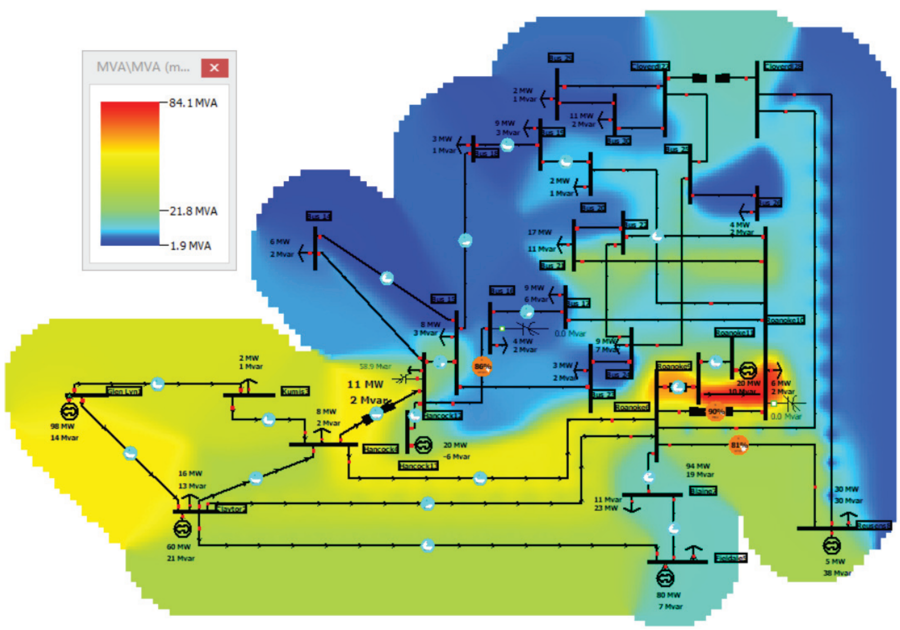


Figure 5.16: Electrical Pulse Simulation Of Local Transmission Load At 5.00s with Bus 12 shunts and explosion center (31,-94)

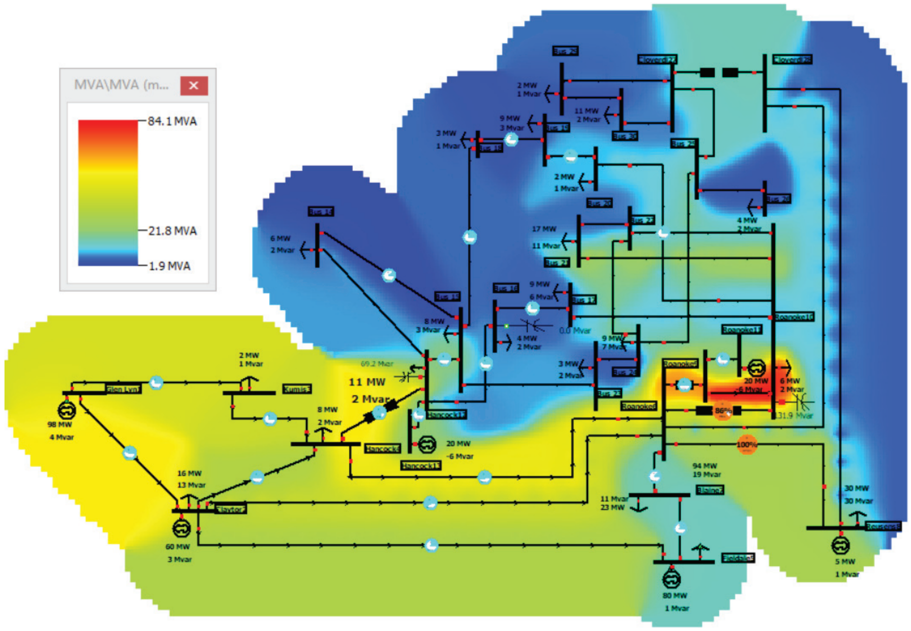


Figure 5.17: Electrical Pulse Simulation Of Local Transmission Load At 5.00s with shunts and explosion center (31,-94)

In Figure 5.14, due to the change of the explosion center point, the transformer overload in original shunt strategy fails. Since the E3 wave intensity of the nuclear electromagnetic pulse is positively correlated with the nuclear weapon equivalent, the existing countermeasures will inevitably fail if the magnetic pulse intensity of the nuclear computer is strengthened. At this point in the power system, the set SVC control shunt still needs to work to alleviate overload and provide adequate response time for possible breaker outage protection. In Figure 5.15 and Figure 5.16, the overload of the power system at 3.59 seconds is relieved due to the SVC control shunt action on the Bus 12. When the pulse time reaches 5 seconds, it can be seen from Figure 5.17 that the alleviating effect of the existing two shunts on overload in the power system has reached its limit. The shunt design provides an additional response time of 1.41 seconds for power system outage operation. This additional response time is much higher than the

0.04 to 0.06 second required for power shunt tripping time, enhancing the power system's ability to respond to sudden nuclear EMP.

In order to obtain the HEMP resilience strategy under different conditions as soon as possible, machine learning can be used to quickly obtain the reasonable response strategy by using the power grid operation state obtained through the SCADA system as input. Because this thesis mainly adopts shunt and scheduling techniques to resist and detract the nuclear electromagnetic pulse, it is necessary to carry out multiple simulations to obtain enough data and use machine learning to obtain the optimal shunt setting and scheduling strategy.[36, 116]

In order to study the resilience strategy of nuclear EMP in power system by machine learning, it is necessary to obtain data from the model according to the overload cause:

1. The data of Nuclear Weapon: The geomagnetic storm-like E3 component of nuclear EMP is more closely proportional to the total energy yield of the weapon, and the E3 wave in a power system is the variation of electric field intensity caused by an electromagnetic pulse. The peak electric field can replace the intensity of the EMP weapon in the E3 wave and the intensity of the impact electric field suffered by each substation. Because of the nuclear electromagnetic pulse propagation process, the Bus coordinates and the explosion center coordinates also need to be set.
2. The Power Flow of regular power system: Since the overload is mainly caused by the current brought by the electromagnetic pulse and the apparent power overload brought by the superposition of the current in the normal power flow operation of the power system, it is necessary to calculate the apparent power flow in the power transmission lines and

transformers during the normal operation of the power system. At the same time, because the electric field pulse generates the pulse current in the conductor of the power system equipment, the resistance and reactance of the transformer need to be counted. The load of the line is not invariable in the actual operation process, and the E1 wave and E2 wave will cause damage to the electronic equipment in the load, so it needs to be set according to the actual situation of the load.

3. The Power Flow of the power system with NEMP: It is the same as normal power system flow, but the power system will be overloaded under HEMP. The apparent power of the lines and transformers at this time can reveal the details of the fault. Because the GIC is the leading cause of the overload in the Power System, the GIC in transformer and transmission line should be the machine learning input data.

4. 4. The Power Flow of the power system with NEMP and shunts: After setting the shunts in the power system with the nuclear EMP, The power flow conditions in the power system have changed, and the overload situation has been alleviated; the power flow conditions need to be re-recorded. At the same time, as the primary measures used in this thesis to resist the nuclear EMP, the shunt data, such as the capacitance unit value, rated reactive power, and actual reactive power should be recorded.

Based on the above data, machine learning training is carried out, and the coordinates of the explosion point of the nuclear electromagnetic pulse, the electric field pulse value, and the load of the power system are taken as input to set the shunt data with the goal of reducing the line load as much as possible.

In order to obtain sufficient data, repeated simulations should be carried out by changing load, explosion center, and electric field pulse intensity to obtain sufficient data. It is planned to subdivide and store the data through a knowledge graph. Force-directed diagrams in Data-Driven Documents(D3) can be used to classify data in different situations. D3 is used to do data visualization, but in this thesis, we mainly use the branch structure of D3 to carry out good statistical data.[78, 84, 85, 107]

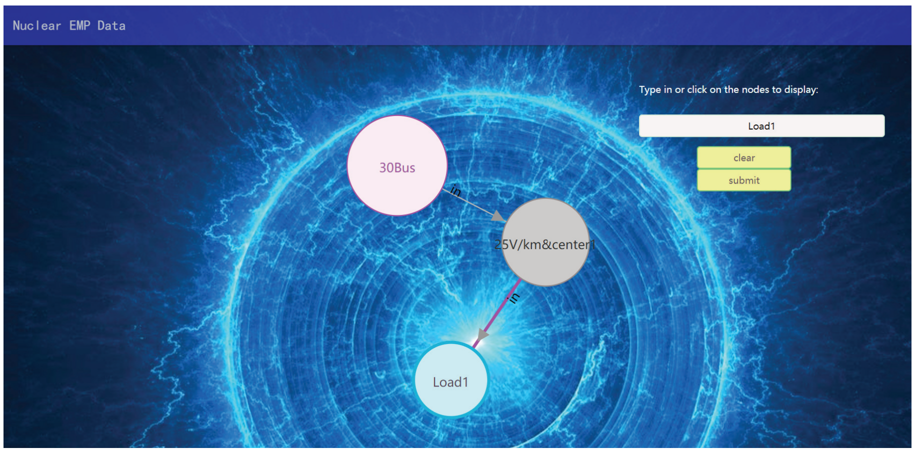


Figure 5.18: Structure of Force-directed diagram

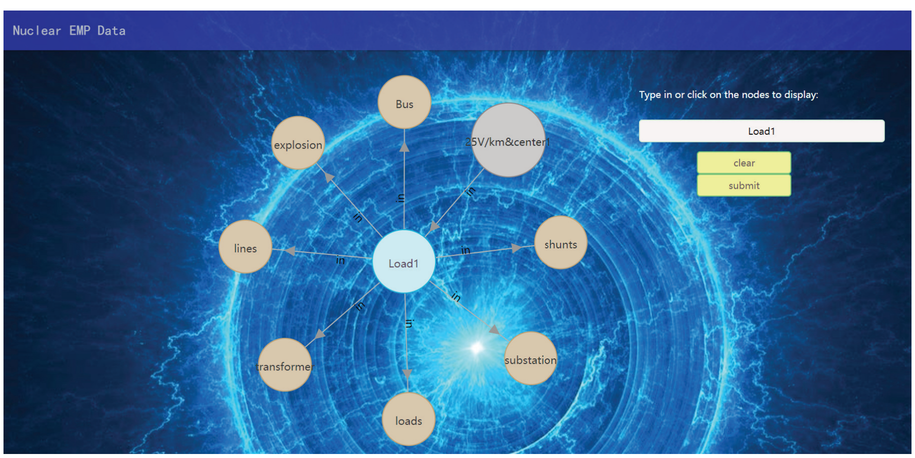


Figure 5.19: NEMP Force-directed diagram input data selection

Figure 5.20: Data classification of NEMP simulation

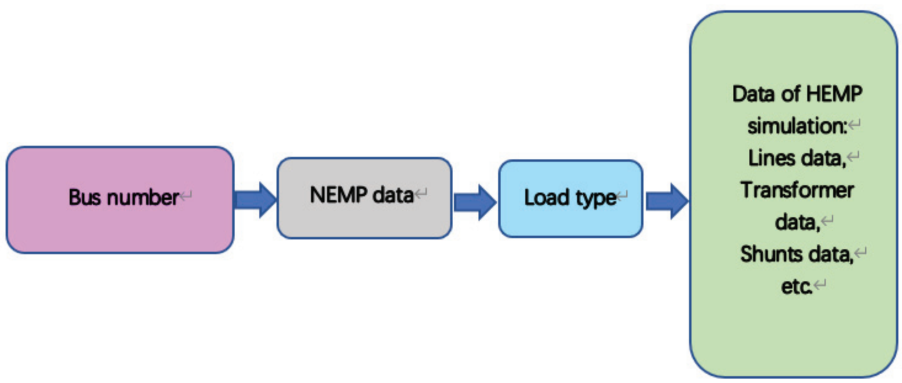


Figure 5.21: Lines Data Download Button

As shown in Figure 5.19, double click the pink, gray, and blue nodes to set the state of the power system, expand the system data and result in classification in Figure 5.20. Double click the brown node marked with data classification to expand the result data in Figure 5.21, and double click the green download node to get the simulation results of the HEMP

In addition to using the D3 force guide diagram to build a database for machine learning in disaster prediction and setting power system resiliency strategy, many equipment manufacturers and patent inventors have improved power transformers to combat HEMP. Siemens, have built transformers capable of withstanding a single pulse of 50 amperes GIC and 200 amperes for a few hours. However, these equipment are more expensive than traditional equipment. It is practical to consider whether it is worthwhile to spend more money to replace special transformers with EMP protection for such rare events as EMP strikes. For the future flexibility strategy, from the equipment level: strengthen the protection of electronic equipment to enhance the power system's operability in E3 wave and continue to study the methods of cheaper transformers against GIC. At the same time, the power plant should adjust the labor in the power system.

5.5 Conclusion

In this chapter, a series of problems related to transformers and resilient strategies for power systems under the EMP attack are discussed. For the transformer, as much as possible to weaken the current in the coil to prevent overload, using the filter with parallel inductance coil to shunt flow in two ways successfully significantly weakened the harmonics, especially the harmfulness of the three most extensive harmonics. However, since the second harmonic and harmonic four still have a higher level, for these two kinds of superposition of harmonic and fundamental wave and flow may lead to the transformer overload concerns, this thesis chooses the improvements on the power system operation and protection. The overcurrent transformers in the system are shunted by reasonable fault removal strategy and SVC shunt so that the power system can withstand the blow of the E3 wave. After adjusting the HEMP explosion point, the simulation shows that the resilience strategy of the power system needs to be changed according to different HEMP attack conditions, so it is necessary to use machine learning to learn and set the elastic strategy. Due to the lack of sufficient data, a sample database of simulation results was designed based on the force-directed diagram of D3 after the discussion of the resilience strategy against nuclear EMP of the power grid and the necessary data types for machine learning. Finally, some new transformers with GIC protection ability are introduced, and the development of EMP flexibility strategy is envisaged.[51, 62]

Chapter 6: Conclusion

6.1 Conclusion

The collapse of the power system will bring about a series of secondary problems that threaten social stability, such as heating shortage, food shortage, and traffic paralysis caused by the lack of power. The power system's scale is unprecedented, so it is incredibly vulnerable to natural and human-made hazards. The power system will become an essential target for hostile forces. In the modern power system, much electronic equipment is composed of the system (such as SCADA) to monitor and control the power network's running state. Nuclear EMP has a wide strike range. Its significant EMP damage can be divided into three stages: E1 and E2, highly destructive to electronic equipment, and E3, highly destructive to electrical equipment. Therefore, the nuclear electromagnetic pulse weapon can attack the modern power system in a wide range and with comprehensive attack equipment. So it is essential to study the resilience strategy of the power system under the EMP attack.

In Chapter 3, to study the damage of the power system after EMP, CST Studio was used to simulate the dry-type transformer. According to the transformer core's soft magnetic characteristic curve, the transformer will face core saturation in the E3 wave. Also, the transformer coil will generate a high amount of induced current. Use the Matlab software to replace the induced current excitation inrush current to carry out harmonic analysis of the saturated transformer.

In Chapter 4, In the fourth chapter, PowerWorld software simulates IEEE30 bus system EMP. Analyze the curve of transformer-induced current and reactive power loss and the curve of substation reactive power loss. The main hazards of the E3 wave to the IEEE30 bus power system are the high induced current in the transmission line and transformer and the reactive power loss in the transformer, and these hazards are concentrated in the first pulse.

Chapter 5 proposes and verifies the resilience strategy for the problems contained in the first two chapters. For the saturated core transformer's harmonics, the harmonic can be significantly reduced using filter and inductor shunt. For the overload phenomenon and reactive power loss in the power system, the cutting overload transformer method can be used to shunt and reduce reactive power loss. Static var compensation(SVC) shunt can also shunt the overload circuit and reactive power compensation to the transformer. Only the above two methods are not ideal in treating transformer reactive power loss, so the power plant can only be used to compensate the system reactive power.

6.2 Resilience Strategy Of Power Grid Against EMP

First, electronic equipment in the grid must be protected by adequate EMP protection. The storage of spare electronic components should be built as close as possible to the electronic equipment room for economic benefit. Ensuring the operation of power electronic equipment or the availability of crucial protection and control equipment is the premise of power equipment against EMP in the power network. When electronic equipment is available, the transmission lines and transformers in the power grid should be kept under load as far as possible to prevent potential fire hazards due to overload. Reasonable shunt design and timely power-off protection can effectively protect the power system from nuclear electromagnetic pulse damage. However, due to the intensity of the nuclear EMP, the location of the explosion center, and the variation of the power system's operating load and power flow, the same protective measures cannot be applied to all the nuclear EMP. Therefore, it is necessary to repeat a power system simulation by adjusting the above parameters to obtain enough data for machine learning. Through machine learning, the resilience strategy of the power grid is set under different nuclear EMP strikes. At the same time, in order to simplify the machine learning data call, using the D3 force guide diagram to build a database to store the simulation results. Therefore, the future grid resilience strategy against nuclear EMP will include the following steps:

1. Detection: The detection methods will be divided into two types: predictable strike and surprise strike. The first is to use defense systems to detect and predict the yield of in-flight and EMP weapons and the specific location and time of the explosion, where the nuclear EMP strike can be predicted. The second is a sudden nuclear electromagnetic strike. There is not enough corresponding time. Because the gamma-ray produces the E1 wave and E2 wave, the gamma-ray intensity is positively correlated with the power of the weapon explosion so that we can calculate the intensity of the electric field pulse generated by the nuclear explosion in the E3 wave by the intensity of the E1 wave and the E2 wave. Satellite observations can determine the location of the explosion.
2. Strategy Making: In a predictable nuclear EMP, because the strike time is not the same as the detection time, it is necessary to predict the power system's load at the strike time to obtain the power flow. After that, by using the predicted strike coordinates, the peak intensity of

electric field pulse of E3 wave and the power load during the strike as the input, a reasonable shunt or power off strategy can be calculated through the trained machine learning. However, for sudden strikes, monitoring equipment such as SCADA system inside the power grid should be used to obtain the load and power flow of the power grid, and the peak intensity of E3 wave electric field pulse obtained after calculation with the results obtained by detectors and the coordinates of explosion point obtained by observation means such as satellites should be used as the input of machine learning to obtain resilience strategies.

3. Power Grid Response: Shunts and circuit breakers in the grid operate on command to avoid grid overloads or delay overloads to break and protect equipment.

4. Restore Normal Power Supply: After the shock and even the disconnected the nuclear electromagnetic pulse hits the power grid, it is closed again, and the regular power supply is restored through the grid dispatching.

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