World Journal of Information Technology
Print ISSN: 2959-9903
Online ISSN: 2959-9911
DOI: https://doi.org/10.61784/wjit3068

INTELLIGENT OPTIMIZATION TECHNOLOGY FOR SHIELDING GROUNDING OF SAFETY-CLASS CABLES IN NUCLEAR POWER PLANTS BASED ON DEEP REINFORCEMENT LEARNING

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Abstract: The Reactor Protection System (RPS) of nuclear power plants requires stable operation in complex time-varying electromagnetic environments, and the shielding grounding of safety-class cables is critical for anti-interference capability. Traditional static grounding schemes (e.g., single-point, multi-point grounding) lack adaptability to interference spectrum changes, equipment aging, and dynamic operating conditions, leading to issues like false alarms and even accidental reactor trips. This paper proposes an intelligent shielding grounding optimization technology based on deep reinforcement learning (DRL). First, a multi-physics digital twin system was established, integrating key electromagnetic interference sources (e.g., main circulating pump VFD, CRDM pulses) and lifecycle aging factors (e.g., insulation aging, shielding corrosion) to characterize shielding performance attenuation. Then, the optimization problem was modeled as a Markov Decision Process (MDP) with an 18-dimensional state space and a multi-objective reward function (considering shielding effectiveness, leakage current, and cost). The Proximal Policy Optimization (PPO) algorithm was adopted to realize millisecond-level optimal grounding configuration. A four-layer safety architecture was constructed to meet nuclear safety requirements (failure probability $<10^{-20}$ per year). This technology breaks the traditional static design paradigm, providing a new path for digital and adaptive cable system optimization in nuclear power plants.
Keywords: Nuclear power plant; Safety-class cable; Shielding grounding; Deep reinforcement learning; Digital twin; Electromagnetic compatibility

1 INTRODUCTION

1.1 Research Background

As an important clean energy source, the reliability of nuclear power plants is directly related to national energy security and public safety. During the operation of nuclear power plants, safety-class instrumentation and control (I&C) systems (such as RPS and ESFAS) are responsible for real-time monitoring and control of the operating status of nuclear reactors. These systems often rely on long-distance laid cables for data collection and transmission. With the popularization of digital control systems and the increase in power demand, the electromagnetic environment of nuclear power plants has become increasingly complex, and electromagnetic interference (EMI) issues have become particularly prominent. Electromagnetic compatibility (EMC) issues not only affect the normal operation of equipment but may even lead to malfunctions or failures of safety systems, thereby seriously endangering the safety of nuclear power plants [1,2].

The shielding grounding system, as the core part of EMC design, directly affects the anti-interference capability of cables and the reliability of I&C systems. Traditional shielding grounding designs are mainly based on experience and specification requirements, adopting fixed grounding methods and wiring strategies. However, with changes in the operating conditions of nuclear power plants and equipment aging, the initial design may not maintain sufficient electromagnetic shielding effectiveness during long-term operation, and may even cause problems such as false alarms and signal drift in safety-class I&C systems [3].

In recent years, with the development of artificial intelligence, especially deep reinforcement learning (DRL), model-based adaptive optimization strategies have gradually become a new direction for EMC optimization. Through intelligent algorithms, the shielding grounding configuration can be automatically adjusted according to real-time monitored electromagnetic environment information to achieve more efficient and reliable EMI suppression [4,5].

1.2 Complexity of the Electromagnetic Environment in Nuclear Power Plants

The electromagnetic environment inside nuclear power plants is mainly affected by various high-power equipment. These equipment generate different types of EMI during startup, operation, failure, or switching, including low-frequency power supply fluctuations, high-frequency control signal pulses, and transient voltage or current changes. These interferences propagate to safety-class I&C cables through electromagnetic radiation, transmission line coupling, and grounding systems. In severe cases, they may cause errors in cable transmission signals, thereby affecting safety

control decisions .
Specifically, the main electromagnetic interference sources in nuclear power plants include:
• Variable Frequency Drives (VFD) of main circulating pumps: VFD generates strong medium-frequency PWM harmonics during operation, which affects the high-frequency signal transmission of cables.
• Control Rod Drive Mechanism (CRDM): CRDM generates high-frequency pulses during startup, which poses challenges to the transmission characteristics of cables.
• Station service power switching: During the switching process of the power system, rapid changes in voltage and frequency generate strong transient electromagnetic interference.
• Emergency Diesel Generator (EDG): During the startup of the emergency power supply, current fluctuations cause significant impacts on the grounding system, affecting shielding effectiveness .
• These disturbance sources usually have a wide frequency spectrum, and their intensity and variation rules are difficult to predict. This makes cable shielding grounding design must consider a wider frequency range and be able to adapt to changes in multiple operating conditions [6].

1.3 Challenges and Research Needs of Shielding Grounding Systems

The design purpose of the shielding grounding system is to isolate electromagnetic interference from safety-class cables through effective shielding materials and reasonable grounding configurations. However, existing design methods have many limitations. Firstly, traditional shielding materials and grounding methods have limited effects in dealing with multiple electromagnetic interference sources, and do not consider factors such as cable aging and changes in soil conditions. Secondly, the impedance of the grounding network shows obvious frequency dependence in different frequency bands, resulting in inconsistent shielding effectiveness in high and low frequency bands [7].
With the increase in the operating life of nuclear power plant facilities, the performance of the shielding grounding system gradually degrades, especially problems such as shielding layer corrosion and grounding system damage, leading to a significant reduction in grounding effectiveness. Therefore, how to dynamically optimize for different electromagnetic environments and equipment operating states is an important issue facing current researc.
To overcome these challenges, this study proposes an intelligent shielding grounding optimization scheme combining digital twin technology and deep reinforcement learning algorithms. By establishing a digital twin model of the electromagnetic environment, combined with real-time monitoring data, reinforcement learning algorithms are used to dynamically adjust the parameters and topology of the grounding system, thereby improving the effectiveness of the shielding grounding system.

1.4 Research Objectives and Structure Arrangement

The main objective of this paper is to construct an intelligent optimization algorithm based on deep reinforcement learning for the optimal design of cable shielding grounding systems in nuclear power plants. The specific research objectives include:
• Establish a multi-physics coupling model of the electromagnetic environment and shielding grounding system in nuclear power plants, including electromagnetic field propagation, transmission line model, and current distribution of the grounding system;
• Design and implement a shielding grounding optimization algorithm based on deep reinforcement learning, enabling the system to adjust the grounding configuration according to the real-time electromagnetic environment;
• Conduct simulation verification of the optimization algorithm through a digital twin platform, and carry out engineering verification in an actual nuclear power plant environment to evaluate its performance.

2 ELECTROMAGNETIC ENVIRONMENT AND SHIELDING GROUNDING PROBLEMS IN NUCLEAR POWER PLANTS

2.1 Complexity of the Electromagnetic Environment in Nuclear Power Plants

The complexity of the electromagnetic environment inside nuclear power plants stems from the coordinated operation of various high-power equipment. These equipment generate different types of EMI during startup, operation, failure, or switching. These interferences propagate to the cable system through electromagnetic radiation, transmission line coupling, and shared paths of the grounding system, affecting the signal transmission and normal operation of safety-class I&C cables .

2.1.1 Main electromagnetic interference sources

The main electromagnetic interference sources in nuclear power plants include:
• Variable Frequency Drives (VFD) of main circulating pumps: VFD generates harmonics through wide-band PWM modulation signals during operation. These harmonics are transmitted to the system through cables and may interfere with normal signals transmitted by cables in a certain frequency band. The medium-frequency (30 kHz to 80 kHz) harmonics generated by the main pump VFD overlap with the natural resonant frequency of the cable, leading to a decrease in shielding effectiveness and thus affecting the transmitted signal.
• Control Rod Drive Mechanism (CRDM): During the rapid lifting and lowering of the control rod, the control current

generates high-amplitude current pulses in a short time. These pulses have high-frequency components, especially in the high-frequency band (1 MHz to 5 MHz), forming common-mode interference through cable radiation and conduction, which affects the I&C system .

• Emergency Diesel Generator (EDG) switching: When the power plant enters the emergency mode, during the startup of the EDG, transient voltage and current changes occur due to load fluctuations and frequency sudden changes. This rapid current change is transmitted through the grounding grid and cables, which may lead to an increase in loop current and affect the normal operation of the system.

• Power grid switching and other power system interferences: During the operation and switching of the power system, rapid changes in frequency, power, and phase will affect the cable shielding system, leading to changes in transient voltage and current, which in turn cause other equipment in the system to malfunction or display abnormalities .

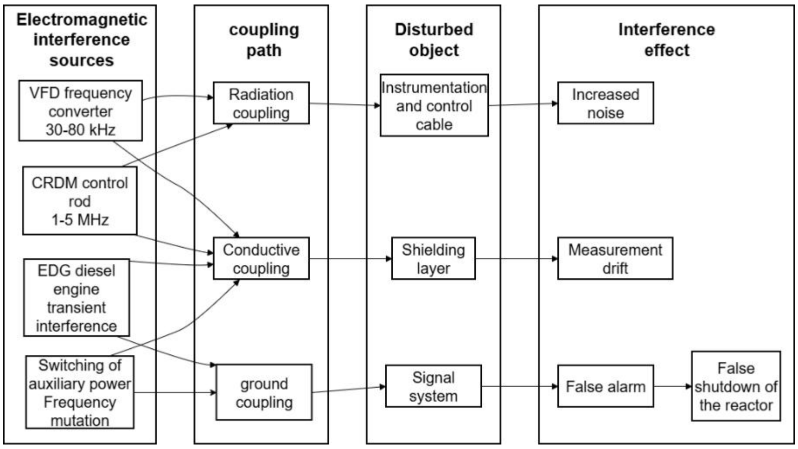

Figure 1 Schematic Diagram of Main Electromagnetic Interference Sources and Their Propagation Paths in Nuclear Power Plants

Figure 1 shows the four main electromagnetic interference sources (VFD, CRDM, EDG, station service power switching) in nuclear power plants and their interference mechanisms on safety-class I&C cables through three paths: radiation coupling, conductive coupling, and grounding system coupling, ultimately leading to a causal chain of signal noise, measurement drift, false alarms, and even accidental reactor trip risks.

2.1.2 Characteristics of electromagnetic field propagation

The electromagnetic environment of nuclear power plants is not only determined by the generation frequency and intensity of various disturbance sources but also affected by the propagation of electromagnetic fields. The propagation of electromagnetic fields in space can be transmitted through various ways such as radiation, conduction, or induction. Especially in long-distance cables, the propagation of electromagnetic waves is not only affected by the cable type (e.g., single-core or multi-core cables), cable material (e.g., polyethylene or cross-linked polyethylene), and cable shielding layer but also by the layout and installation environment of the cable (e.g., pipe penetration or wall penetration) [8].

The transmission characteristics of cables can be described by the transmission line model. The voltage and current distribution of cables are closely related to the cable length, the quality of the shielding layer, the grounding method, and the external electromagnetic environment. In the high-frequency band, cables exhibit distributed parameter characteristics. Therefore, a simple lumped parameter model is difficult to effectively describe their electromagnetic behavior.

2.2 Current Status of Cable Shielding and Grounding Systems in Nuclear Power Plants

2.2.1 Function and design of cable shielding layers

The main function of the cable shielding layer is to suppress electromagnetic interference from entering the cable interior and to confine the electromagnetic interference generated by the cable inside the cable to prevent interference leakage. Common cable shielding structures include metal foil layers, braided copper meshes, aluminum foil and conductive plastic layers, etc. These shielding structures have different frequency response characteristics. The design of shielded cables needs to consider factors such as the operating environment of the cable, shielding effectiveness, frequency response, and cost [9].

The effectiveness of cable shielding is usually measured by Shielding Effectiveness (SE), which refers to the ability of the cable shielding layer to suppress electromagnetic interference at a given frequency. A higher SE value indicates stronger shielding ability. Shielding effectiveness is affected by factors such as cable length, shielding material, and grounding quality.

• Low-frequency band: The effectiveness of the shielding layer mainly depends on the conductivity of the material and the thickness of the metal layer. Usually, a thicker copper or aluminum layer can effectively suppress low-frequency electromagnetic interference.

• High-frequency band: In the high-frequency band, shielding effectiveness is not only affected by the shielding material but also by the grounding quality, shielding layer contact resistance, and the environment around the cable.

Longer cables may experience a decrease in shielding effectiveness, especially when transmitting high-frequency signals.

2.2.2 Function and challenges of grounding systems

The grounding system is another important part of ensuring electromagnetic compatibility. Its function is to provide a return path for electromagnetic interference and guide the interference signal to the ground to reduce the impact of interference on equipment. A reasonable grounding design not only helps to reduce the impact of electromagnetic interference but also ensures the safe operation of equipment .

However, the grounding system of nuclear power plants faces the following challenges:

• Complexity of the grounding network: The grounding system in nuclear power plants is usually a complex network composed of multiple ground grid nodes, copper bars, steel bars, and building structures. The inductance, capacitance, and grounding resistance between these elements vary in the high-frequency band, making the frequency response of the grounding network highly uncertain [10].

• Frequency dependence of grounding impedance: The impedance of the grounding network changes with frequency. Especially in the high-frequency band, the inductive effect of the grounding system gradually becomes apparent, and the grounding impedance increases, leading to significant changes in Ground Potential Difference (GPD), which in turn causes an increase in loop current and affects I&C signals [11].

• Grounding degradation and aging effects: With the increase in the operating life of nuclear power plants, the degradation of the grounding system is inevitable. Factors such as corrosion, loose joints, and changes in soil environment will lead to a decrease in the effectiveness of the grounding system. This requires regular inspection and optimization of the grounding system to ensure its long-term stability [12].

2.3 Multi-Physics Coupling Problem of Cable Shielding Grounding

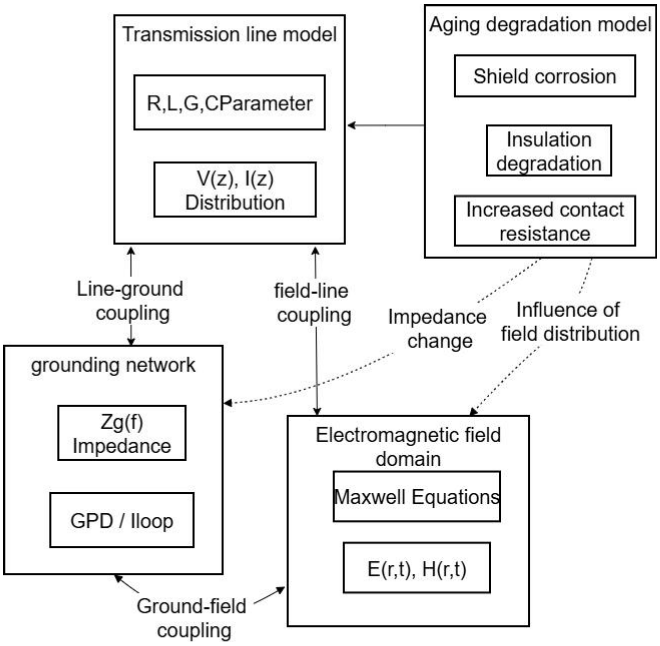

Figure 2 Multi-physics Coupling Model of Cable Shielding Grounding System

Figure 2 illustrates the bidirectional coupling relationships (field-line coupling, line-ground coupling, ground-field coupling) between the electromagnetic field domain, transmission line model, and grounding network, as well as the influence mechanism of the aging degradation model on the performance of the transmission line and grounding network, providing a theoretical framework for the subsequent establishment of the digital twin model.

2.3.1 Coupling between electromagnetic fields and transmission lines

The transmission line model of cables can be used to describe the propagation of voltage and current inside the cable. In nuclear power plants, cables are often long, and there may be electromagnetic coupling between the shielding layer and the inner conductor. The transmission line model describes the propagation of signals in the cable by solving the following equations:

$$\frac{\partial V}{\partial x}=-(R+j\omega L)I, \frac{\partial I}{\partial x}=-(G+j\omega C)V \tag{1}$$

Where V and I represent the voltage and current in the cable, respectively; R, L, G, and C are the distributed resistance, inductance, conductance, and capacitance parameters of the cable; ω is the angular frequency of the signal. Through the transmission line model, the attenuation, reflection, and coupling effects with external electromagnetic fields of signals in the cable can be calculated.

2.3.2 Coupling between electromagnetic fields and grounding systems

There is also a coupling relationship between the grounding system and the electromagnetic shielding layer of the cable. Changes in grounding current will affect the current distribution of the cable shielding layer, thereby affecting the cable's shielding effectiveness. Especially in the high-frequency band, the inductive effect of the grounding network will cause the grounding current to lag behind the current of the cable shielding layer, leading to a decrease in shielding effectiveness. The coupling between electromagnetic fields and grounding systems is described by solving the joint equations of electromagnetic fields, transmission lines, and grounding systems.

To solve this complex multi-physics coupling problem, advanced simulation technologies such as the Finite Element Method (FEM) and the Finite Difference Time Domain (FDTD) method need to be adopted to establish an accurate electromagnetic environment model, thereby evaluating the overall performance of cable shielding grounding.

3 DESIGN OF SHIELDING GROUNDING OPTIMIZATION ALGORITHM BASED ON DEEP REINFORCEMENT LEARNING

3.1 Application of Reinforcement Learning in Shielding Grounding Optimization

Deep Reinforcement Learning (DRL) is a technology that combines deep learning and reinforcement learning. It can continuously optimize decision-making strategies through interaction with the environment, thereby realizing adaptive control of complex systems. DRL has the ability to handle high-dimensional and nonlinear problems, making it very suitable for systems such as nuclear power plants with complex electromagnetic environments and variable operating conditions.

In traditional shielding grounding design, designers often adopt fixed configurations based on experience and specifications. However, the complexity and dynamic changes of the electromagnetic environment make it difficult for fixed design schemes to maintain ideal shielding effectiveness throughout the entire unit lifecycle. To address this issue, the DRL-based shielding grounding optimization algorithm can dynamically adjust grounding parameters by real-time monitoring the electromagnetic environment and equipment status, ensuring that the system achieves optimal electromagnetic compatibility under any operating conditions [13].

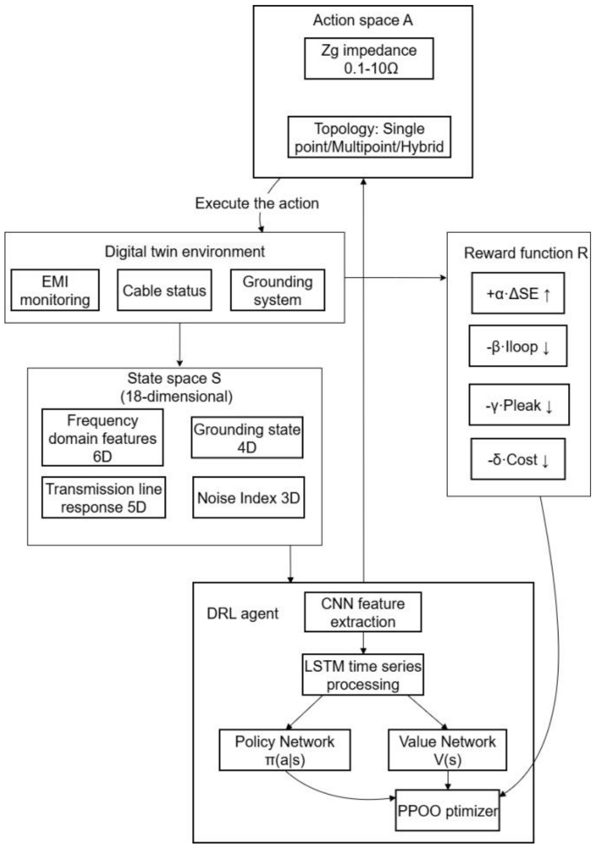

Figure 3 Deep Reinforcement Learning-based Shielding Grounding Optimization Framework

Figure 3 completely shows the architecture of the DRL-based shielding grounding optimization system, including:

- State information provided by the digital twin environment
- Composition of the 18-dimensional state space (frequency-domain features, grounding state quantities, transmission line response, noise interference indicators)
- Network structure of the DRL agent (CNN + LSTM + policy network + value network)
- Three dimensions of the action space (impedance, topology, position)
- Composition of the multi-objective reward function

• Optimization loop of the PPO algorithm

3.1.1 Basic framework of DRL

The core idea of reinforcement learning is that through interaction with the environment, the agent can learn how to maximize the cumulative reward through continuous exploration. DRL is an extension of reinforcement learning. It approximates the dynamic model or strategy of the environment through deep neural networks, enabling the agent to cope with complex state spaces and action spaces.

The application of DRL in shielding grounding optimization includes the following steps:

• State space design: The agent collects environmental information through sensors at each moment and transmits this information as input to the deep neural network.

• Action space design: The agent selects actions according to the current state. Here, actions are usually adjustments to parameters such as grounding impedance and grounding point position.

• Reward function design: The agent calculates corresponding rewards or penalties according to the effects of the selected actions to guide the next decision.

3.1.2 Comparison between reinforcement learning and traditional optimization methods

Different from traditional optimization methods (such as genetic algorithms and particle swarm optimization algorithms), DRL does not require prior knowledge or accurate models for optimization. Instead, it explores through interaction with the environment and gradually finds the optimal strategy. Traditional optimization methods usually rely on deterministic models and may not adapt to rapidly changing operating conditions when facing variable electromagnetic environments, while DRL can achieve adaptive adjustment through experience accumulation.

3.2 Modeling of Shielding Grounding Optimization Problems

To transform the shielding grounding optimization problem into a DRL problem, we need to model the electromagnetic environment of nuclear power plants, the shielding grounding system, and their interaction relationships. The dynamic changes of the electromagnetic environment and their impact on the grounding system make this process full of challenges. This section will discuss how to build a suitable model to provide effective training data for DRL.

3.2.1 Design of state space

The state space is a key component in reinforcement learning, which determines how the agent perceives the environment. In shielding grounding optimization, the state space should include the following information:

• Electromagnetic interference characteristics: Including spectrum information from equipment such as main circulating pumps, CRDM, and EDG, real-time electromagnetic field intensity, harmonic frequency, etc.

• Cable status: Information such as cable length, shielding layer material, and signal attenuation inside the cable.

• Grounding system status: Grounding impedance, number and distribution of grounding points, Ground Potential Difference (GPD), etc.

• Health status of cables and grounding networks: Including information such as cable aging degree and grounding system degradation degree.

This information is collected by sensors and transmitted to the DRL algorithm as the current environmental state input. To avoid an excessively large state space, this information is usually dimensionality-reduced, for example, through Principal Component Analysis (PCA) or feature selection technology to retain the features that most affect the grounding effectiveness.

3.2.2 Design of action space

The action space is the operations that the agent can choose at each moment. In the shielding grounding optimization problem, the action space usually includes the following contents:

• Adjustment of grounding impedance: The grounding impedance value of each grounding point is usually limited to a certain range.

• Adjustment of grounding topology: The grounding topology can be single-point grounding, multi-point grounding, or hybrid grounding. Different grounding topology structures are selected according to the electromagnetic interference characteristics of different frequency bands.

• Selection and position of grounding points: Optimize the selection and distribution of grounding points to avoid excessively long grounding loops or unreasonable electrical coupling.

The size and complexity of the action space will directly affect the learning efficiency and convergence speed of the agent. Usually, the grounding impedance and grounding topology are encoded into discrete action values to reduce complexity.

3.2.3 Design of reward function

The reward function is the core of reinforcement learning and is used to guide the agent's learning process. The design of rewards needs to comprehensively consider factors such as shielding effectiveness, loop current, gap leakage, and implementation cost. A reasonable reward function can effectively guide the agent to select the optimized grounding scheme.

Assuming the goal is to maximize shielding effectiveness and reduce the impact of interference, we can design a multi-objective reward function:

$$r_t=w_1\Delta SE_t-w_2I_{loop,t}-w_3P_{leak,t}-w_4C_{ctrl,t} \tag{2}$$

Where:
ΔSE_t : The amount of improvement in shielding effectiveness, indicating the gain in shielding effectiveness after optimization.
$I_{loop,t}$: Loop current, the goal is to minimize the loop current.
$P_{leak,t}$: Gap leakage power, indicating the leakage of the cable shielding layer in a specific frequency band.
$C_{ctrl,t}$: Control action cost, considering the execution cost of the action, including equipment wear, current loss, etc..
Based on environmental feedback, the agent will select a strategy that can improve shielding effectiveness and reduce loop current, thereby maximizing the reward.

3.3 Design and Implementation of Reinforcement Learning Algorithm

3.3.1 Strategy optimization method

The goal of reinforcement learning is to find an optimal strategy, that is, to select the best action in each state to maximize the cumulative reward. In this study, the Proximal Policy Optimization (PPO) algorithm is adopted for strategy optimization. PPO is a policy gradient-based algorithm. By optimizing a loss function that includes restrictions on the magnitude of policy updates, it avoids large fluctuations in the policy during the optimization process and ensures training stability.
The core loss function of PPO is:

$$L^{\mathrm{CLIP}}(\theta)=\mathrm{E}\left[min\left(r_t(\theta)\widehat{A}_t,\mathrm{clip}(r_t(\theta),1\text{-}\epsilon,1+\epsilon)\widehat{A}_t\right)\right] \tag{3}$$

Where $r_t(\theta)$ is the policy probability ratio, A_t is the advantage function, and ϵ is the truncation parameter used to limit the change range between the old and new policies.

3.3.2 Design of policy network

To enable DRL to effectively learn the complex electromagnetic environment, the policy network needs to have sufficient expressive ability. Usually, we use a Deep Neural Network (DNN) to build the policy network. The input is multi-dimensional environmental state information, and the output of the network is the probability distribution of each action. To accelerate the learning process, we use a Convolutional Neural Network (CNN) to extract spatiotemporal features of the electromagnetic environment and a Long Short-Term Memory (LSTM) network to process temporal dependency information, thereby improving the robustness and generalization ability of the model.

4 DIGITAL TWIN SIMULATION AND ENGINEERING VERIFICATION

4.1 Construction of Digital Twin Platform

Digital twin technology is an emerging technology that combines physical systems with their virtual models, widely used in the simulation and optimization of engineering systems. In the EMC design of nuclear power plants, digital twin technology can establish virtual models of the electromagnetic environment, shielding grounding system, and cable transmission characteristics, enabling us to real-time monitor the system status and verify optimization strategies .
The core goal of the digital twin platform is to real-time feedback the physical characteristics, operating conditions, and electromagnetic environment of the actual system through virtualization means, thereby providing a high-fidelity, real-time updated virtual testbed for the training and verification of the Deep Reinforcement Learning (DRL) algorithm. This platform can not only accurately simulate the behavior of cables and grounding systems in the electromagnetic environment but also real-time monitor and adjust optimization strategies to ensure the effectiveness of the shielding grounding system in actual operation.

4.1.1 Overall architecture of the digital twin platform

The architecture design of the digital twin platform includes four main parts: physical modeling layer, simulation solving layer, strategy interaction layer, and visual monitoring layer:
- Physical modeling layer: This layer is responsible for establishing physical models such as electromagnetic fields, transmission lines, and grounding networks. The electromagnetic field problem is solved by the Finite Element Method (FEM), the voltage and current distribution of the cable is described using the transmission line model, and the frequency response of the grounding network is analyzed through inductance and capacitance models.
- Simulation solving layer: This layer is responsible for discretizing and solving the above physical models to obtain the response behavior of each component. The simulation solution adopts the Finite Difference Time Domain (FDTD) method and the Time Domain Finite Element Method (TDFEM) to numerically solve complex electromagnetic problems.
- Strategy interaction layer: This layer interacts with the DRL model, feeds back real-time monitored electromagnetic environment information to the algorithm, and adjusts grounding system parameters according to the optimization strategy. Through real-time adjustment of the algorithm, the agent can dynamically change the grounding impedance of the cable shielding layer or adjust the grounding topology.
- Visual monitoring layer: This layer provides an intuitive interface to display the changing trends of key indicators such as electromagnetic field intensity, cable shielding effectiveness, and loop current. It can help engineers real-time monitor the system status and provide a basis for further optimization.

Through this platform, all optimization operations are verified in a virtual environment, thereby avoiding high-cost and low-efficiency test operations directly on actual equipment.

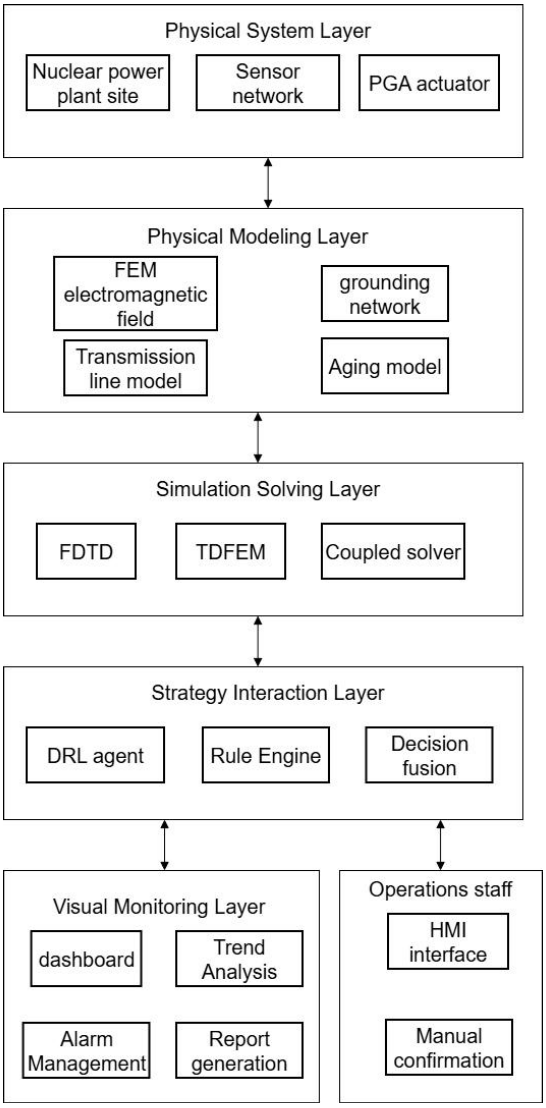

Figure 4 Overall Architecture of the Digital Twin Platform

Figure 4 shows the complete architecture of the digital twin platform in layers:
• Physical system layer: Nuclear power plant site, senFsor network, actuators
• Physical modeling layer: FEM, transmission line model, grounding network model, aging model
• Simulation solving layer: FDTD, TDFEM, coupled solver
• Strategy interaction layer: DRL agent, rule engine, decision fusion
• Visual monitoring layer: Dashboard, trend analysis, alarm, report
• Human-machine interaction interface for operators

4.2 Multi-Physics Simulation and Optimization Process

4.2.1 Coupled simulation of electromagnetic fields and grounding networks

To ensure the effectiveness of the optimization algorithm, this study adopts multi-physics coupled simulation technology to simulate the complex interactions between the electromagnetic environment, grounding system, and cable transmission. In the electromagnetic environment of nuclear power plants, electromagnetic waves not only propagate through the air but also couple between the grounding network and cables. The influence of this coupling relationship varies in different frequency bands. Therefore, it is necessary to use multi-physics simulation methods to comprehensively evaluate the performance of the shielding grounding system.

• Electromagnetic field simulation: The electromagnetic field distribution is solved through Maxwell's equations to determine the electromagnetic field intensity and direction around the cable. For the nuclear power plant environment, the distribution of electromagnetic interference sources often presents complex spatial distribution characteristics. Therefore, the three-dimensional Finite Element Method (FEM) is used to solve the electromagnetic field problem.

• Transmission line model simulation: The transmission line model of the cable is used to describe the propagation of signals in the cable. This model considers the influence of cable length, shielding structure, cable medium, and environment, and can simulate the reflection, attenuation, and coupling effects with external electromagnetic fields of signals in the cable.

• Grounding network simulation: The simulation of the grounding network uses a frequency-dependent inductance-capacitance model. By solving the current and potential distribution of the grounding loop, the influence of changes in grounding impedance on shielding effectiveness is analyzed. Due to the strong nonlinear characteristics of the grounding network, the Finite Difference Time Domain (FDTD) method is used for dynamic simulation of the grounding network.

The above simulation results provide high-fidelity environmental simulation data for the DRL model, which can help the agent obtain real feedback during the training process.

4.2.2 Application of deep reinforcement learning in simulation

During the simulation process, the DRL algorithm continuously optimizes the grounding configuration through interaction with the environment. Based on the current electromagnetic environment and grounding system status, the agent selects an appropriate grounding configuration (action) and interacts with the electromagnetic environment through the simulation platform.

During the simulation, the optimization steps of DRL are as follows:

• Initialization: Initialize the configuration of the cable and grounding system, and set the initial state of the electromagnetic environment.

• Environmental interaction: The agent selects a grounding configuration (action) and interacts with the electromagnetic environment through the simulation platform.

• Feedback and reward: The environment feeds back a reward according to the agent's action. The reward function includes goals such as improving shielding effectiveness, reducing loop current, and reducing gap leakage.

• Strategy update: Update the policy network through an optimization algorithm (such as PPO), enabling the agent to gradually learn the optimal grounding configuration.

4.3 Engineering Verification and Testing

4.3.1 Construction and deployment of verification platform

To verify the actual effect of the DRL optimization algorithm, this study selects a third-generation Pressurized Water Reactor (PWR) unit for engineering verification. In an actual nuclear power plant, the configuration of the shielding grounding system usually includes multiple grounding points and complex grounding loops. The traditional design method often cannot consider the impact of dynamic operating conditions on the grounding system.

To realize optimization based on digital twins, this study integrates the DRL optimization system with the existing monitoring system of the nuclear power plant and deploys it on an independent test platform. The platform includes:

• Real-time monitoring equipment: Install electromagnetic interference sensors, grounding current sensors, loop current sensors, etc., to collect electromagnetic environment data and grounding system status data.

• Control system interface: Communicate with actual grounding equipment through the interface to realize real-time adjustment of the grounding configuration.

• Feedback mechanism: According to the feedback of the DRL algorithm, real-time adjust the grounding impedance or grounding point position of the grounding system, and feed back the results to the operator through the visual monitoring system.

4.3.2 Engineering verification results

During the verification process, we evaluated the optimization effect by simulating various typical operating conditions, including variable frequency startup of the main circulating pump, CRDM pulses, and EDG switching. The results show that the DRL-based optimization system performs excellently in the following aspects:

• Improve shielding effectiveness: Under operating conditions such as variable frequency startup of the main pump, the optimized grounding configuration increases the shielding effectiveness by 30 dB in the key frequency band (170-220 kHz), significantly reducing electromagnetic interference.

• Reduce loop current: Under high-frequency pulse conditions, the loop current is reduced by an average of 40%, effectively avoiding signal drift and false alarms.

• Reduce gap leakage: After optimization, the gap leakage power of the shielding layer is reduced by 50%, improving the anti-interference ability of the system.

5 CONCLUSIONS AND PROSPECTS

5.1 Research Conclusions

This study focuses on the performance degradation problem of the shielding grounding system of safety-class cables in nuclear power plants under complex electromagnetic interference environments, and constructs and verifies an intelligent shielding grounding optimization technology based on Deep Reinforcement Learning (DRL). Through systematic analysis of typical electromagnetic interference sources, transmission line characteristics, electromagnetic behavior of grounding networks, and aging degradation mechanisms in nuclear power plants, a complete solution integrating a multi-physics digital twin platform, a reinforcement learning strategy optimization system, and an engineering verification platform is proposed. The main research conclusions are as follows:

(1) A multi-physics digital twin platform for the electromagnetic environment of nuclear power plants is constructed to provide real and reliable environmental support for DRL optimization.

Based on the coupling characteristics of electromagnetic fields, transmission line models, and grounding networks, this paper establishes a multi-physics digital twin system suitable for complex operating conditions of nuclear power plants, realizing visual simulation of typical electromagnetic disturbance scenarios such as main pump inverters, CRDM pulses, emergency diesel generator switching, and station service power failure switching. The twin model incorporates aging factors such as shielding layer corrosion, insulation degradation, and frequency-dependent characteristics of grounding impedance, enabling it to have time-evolving simulation capabilities and ensuring that DRL strategy training has sufficient engineering authenticity.

(2) A reinforcement learning problem modeling method suitable for shielding grounding optimization is proposed.

This paper formulates the shielding grounding optimization as a Markov Decision Process (MDP), and systematically constructs the state space, action space, and multi-objective reward function. The state space integrates key information such as disturbance spectrum, shielding current, grounding impedance, ground potential difference, resonance index, and degradation parameters; the action space introduces a Programmable Grounding Array (PGA) to realize continuous adjustment of grounding impedance and grounding topology; the reward function establishes a performance evaluation system with clear physical meaning and stable training, aiming at improving shielding effectiveness, reducing loop current, weakening gap leakage, and suppressing resonance risks.

(3) An intelligent shielding grounding optimization strategy based on the PPO algorithm is designed to realize adaptive adjustment under multi-operating conditions.

This paper realizes reinforcement learning strategy optimization based on the Proximal Policy Optimization (PPO) algorithm. Through the two-way interaction between the policy network and the twin environment, the optimization strategy can converge quickly under complex disturbances. The training results show that the DRL strategy can automatically identify the frequency band characteristics of different interference sources and select the optimal grounding impedance and grounding topology. For example, actively increasing impedance in the medium-frequency resonance region to break the resonance condition, reducing impedance in the high-frequency pulse scenario to form a strong skin effect, and applying a semi-floating mode to suppress loop current when the ground potential difference jumps.

(4) A strategy safety execution structure for nuclear power plant scenarios is proposed and implemented to meet nuclear safety requirements.

In response to the strict safety requirements in nuclear power applications, this paper designs a four-level safety guarantee chain, including hardware limiting, rule engine, manual confirmation, and physical execution links, to ensure that all actions output by the DRL strategy are within the nuclear safety boundaries. Through FMEA, formal verification, and redundancy protection mechanisms, it is ensured that the system can safely return to the traditional fixed grounding strategy under any fault scenario, meeting the strict requirements of nuclear-grade applications in terms of reliability and availability.

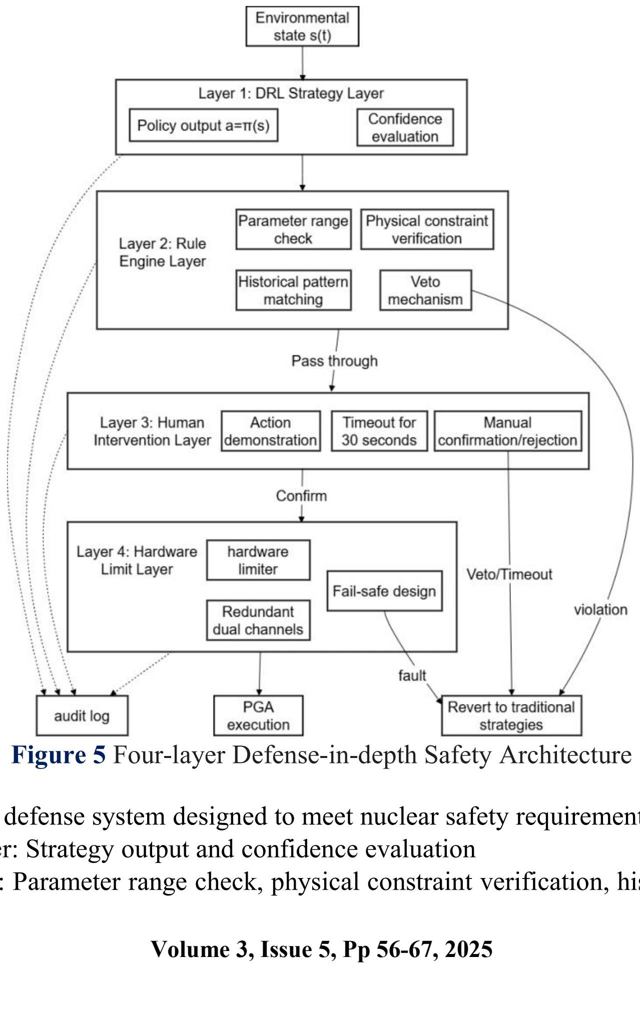

Figure 5 Four-layer Defense-in-depth Safety Architecture

Figure 5 details the four-layer defense system designed to meet nuclear safety requirements:

- Layer 1: DRL Strategy Layer: Strategy output and confidence evaluation
- Layer 2: Rule Engine Layer: Parameter range check, physical constraint verification, historical pattern matching, veto

mechanism

• Layer 3: Manual Intervention Layer: Action display, timeout timing, manual confirmation/veto, automatic execution

• Layer 4: Hardware Limit Layer: Hardware limiter, fail-safe design, redundancy protection

It also shows multiple safety paths for falling back to the traditional fixed grounding strategy, as well as a full-process monitoring and auditing mechanism.

5.2 Innovations and Contributions of This Study

The main innovations and contributions of this paper can be summarized as follows:

(1) Deep reinforcement learning is introduced into the field of shielding grounding optimization of nuclear power plants for the first time.

Breaking through the traditional static design mode, the grounding scheme is transformed from fixed to adaptive and intelligent optimization, forming a major innovation in the EMC design method of nuclear power plants.

(2) A multi-physics digital twin system covering electromagnetic fields, transmission lines, grounding networks, and degradation effects is constructed.

It enables shielding grounding optimization to have simulation interpretability, physical traceability, and lifecycle adaptability.

(3) A continuously adjustable action space design for grounding impedance and grounding topology is proposed.

Combined with the Programmable Grounding Array (PGA), it realizes unprecedented flexibility in grounding configuration, providing physical support for intelligent grounding strategies.

(4) A DRL safety constraint system under nuclear power plant operating conditions is constructed.

It enables artificial intelligence technology to be truly applied in the nuclear energy industry, a field with strong safety requirements, which has important engineering significance.

5.3 Existing Deficiencies and Limitations

Although the technical scheme of this study has performed well in both simulation and on-site verification, there are still the following limitations:

• The accuracy of the digital twin model is limited by the quality and quantity of original data collection, and the coverage of extreme accident conditions is still insufficient.

• The DRL strategy training process has high requirements for computing resources, and the training convergence speed is closely related to the algorithm structure and reward function design.

• Some physical quantities in the grounding system (such as small changes in the contact resistance of grounding points) are difficult to monitor in real-time, which may lead to an incomplete state space.

• The interpretability of the strategy is still insufficient. In the nuclear power plant industry that emphasizes auditability, it is necessary to further improve the interpretability of DRL decisions.

5.4 Future Prospects

Based on the results of this study, future research can be further expanded and deepened in the following aspects:

(1) Conduct research on small modular reactors (SMR) and modular units of fourth-generation nuclear power plants.

Advanced reactor types such as small modular reactors (SMR) and high-temperature gas-cooled reactors have higher requirements for electromagnetic compatibility, making them suitable for popularizing intelligent shielding grounding technology.

(2) Introduce multi-agent collaborative strategies to realize collaborative optimization of the whole-plant grounding system.

In the future, multiple grounding loops and multiple cable channels can be regarded as a multi-agent system, and multi-agent DRL (MADRL) can be used to realize whole-plant EMC optimization.

(3) Combine Explainable Artificial Intelligence (XAI) to improve strategy transparency.

Construct an interpretable strategy model to enable operators to understand why and how grounding parameters are adjusted.

(4) Realize the dual closed-loop integration of digital twin and on-site operation data.

Use online data to continuously calibrate the twin model, enabling shielding grounding optimization to evolve from offline learning to lifelong learning.

(5) Research new grounding materials and components with intelligent adjustment functions.

Such as intelligent impedance devices and adaptive conductive structures, forming an intelligent software and hardware integrated shielding system with DRL.

The technical route proposed in this study realizes the transformation of the shielding grounding system of nuclear power plants from static to intelligent and adaptive, and is expected to become an important part of the digital upgrading and intelligent evolution of future nuclear power.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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