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Research and Application of EMC Design in the Cabinet Project for the Absorber Ball Shutdown Drive Mechanism of High-Temperature Reactors

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Abstract

Stepper motor drivers constitute the primary equipment within the absorber ball shutdown drive mechanism cabinets of high-temperature gas-cooled reactor nuclear power plants, utilizing PWM pulse width modulation technology. The high-order harmonic components produced during the pulse width modulation process reciprocally influence the operational stability and precision of the drivers; under severe conditions, this may induce unintended dropping of absorber balls, thereby affecting the normal operation of the nuclear power plant, or cause refusal of absorber balls to drop, compromising nuclear safety. Through comprehensive investigation into the operating mechanism, transmission pathways, and impact severity of interference generated by PWM pulse width modulation, the customized design and strategic placement of appropriate reactors and filters along interference source transmission paths can effectively block interference propagation and mitigate its impact. Concurrently, through optimized cabinet wiring, adoption of suitable signal communication cables, and implementation of reliable grounding, among other integrated measures, the detrimental effects of the driver's PWM pulse width modulation mechanism on weak electrical signals transmitted over long distances can be effectively resolved, enabling stable operation of stepper motors and enhancing system operational reliability and safety.

Full Text

Research and Application of Anti-Interference Design in the Drive Cabinet Project of the Absorption Sphere Shutdown System for High-Temperature Reactors

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Abstract

The stepper motor driver is the primary equipment in the absorption sphere shutdown drive mechanism cabinet of high-temperature gas-cooled reactor nuclear power plants. Employing PWM (Pulse Width Modulation) technology, the high-order harmonic components generated during the modulation process adversely affect the driver's operational stability and precision. In severe cases, this may cause the absorption sphere to drop erroneously, impacting normal power plant operation, or refuse to drop, affecting nuclear safety. Through in-depth research on the mechanism, transmission paths, and impact magnitude of interference caused by PWM, custom-designed reactors and filters can be strategically placed along the interference source transmission paths to effectively block interference propagation and suppress its effects. Concurrently, by optimizing cabinet wiring, employing appropriate signal communication cables, and implementing reliable grounding, the impact of the driver's PWM modulation mechanism on weak electrical signals transmitted over long distances can be effectively resolved, ensuring stable stepper motor operation and enhancing system reliability and safety.

Keywords: Stepper motor driver; Interference; Pulse width modulation; Electromagnetic compatibility; Harmonics

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Introduction

The High Temperature Gas-Cooled Reactor Pebble-Bed Modules (HTR-PM) demonstration nuclear power plant employs a three-phase hybrid stepper motor to drive a ball screw mechanism in its absorption sphere shutdown system, executing the function of dropping absorption spheres for reactor shutdown. The stepper motor must demonstrate long-term reliable operation with smooth performance, no abnormal noise, and high precision in driving the ball screw for forward rotation, reverse rotation, and position holding. The stepper motor driver, as the primary equipment in the absorption sphere shutdown drive

mechanism cabinet, utilizes PWM (Pulse Width Modulation) technology. However, the PWM output contains substantial high-order harmonic components that pollute and impact the power grid and grounding system, representing a significant industry challenge. While stepper motor drivers are widely used in automation fields such as woodworking engraving machines, CNC machine tools, glass machinery, computer embroidery machines, and laser cutting machines—where the operating environment is relatively favorable and the distance between driver and motor is short—the adverse effects of high-order harmonic components from PWM output are not readily apparent. In the HTR-PM demonstration project, the considerable distance between the driver and stepper motor necessitates comprehensive evaluation and preventive measures for the combination of PWM modulation and long-distance transmission. Constrained by project schedules and other factors, the anti-interference design must be implemented under specific limitations. Through theoretical analysis to identify interference sources and transmission paths, combined with experimental acquisition of quantitative data, specially designed filters and reactors with strictly matched performance parameters were developed to block interference sources and achieve anti-interference objectives.

System Structure and PWM Principle

The stepper motor driver in the absorption sphere shutdown drive mechanism receives pulse signals from the upstream Distributed Control System (DCS) or the local cabinet, controlling the motor's speed and rotation angle through the sequence, frequency, and quantity of electrical pulses [2,4,11]. The signal cable from the DCS cabinet to the driver, measuring 70 meters in length, transmits weak electrical pulse signals, while the power cable from the driver to the motor, spanning 50 meters, delivers three-phase 380V power. The system architecture is illustrated in Figure 1 [Figure 1: see original paper].

The stepper motor driver operates based on pulse width modulation principles [5-6]. As shown in Figure 2 [Figure 2: see original paper], the driver receives weak voltage-type pulse commands, rectifies the input 220VAC (as shown in Figure 2(a)) into direct current, and then inverts and modulates it into a high-voltage square wave signal (Figure 2(b)). The quantity of these square wave signals corresponds one-to-one with the received weak voltage pulses, while the pulse width is controlled by the driver's subdivision setting parameters. The stepper motor's rotation angle and operating speed match the square wave signals shown in Figure 2(b). This operating mode offers significant advantages in energy efficiency, environmental protection, cost reduction, and quality improvement.

The working principle of Pulse Width Modulation (PWM) involves controlling the on-off switching of inverter circuit devices to produce a pulse sequence with equal amplitude at the output, using these pulses to replace sinusoidal wave output. During high-speed switching, power switching devices exhibit extremely high voltage change rates (dv/dt), reaching up to $20,000 \text{ V} \cdot \text{s}^{-1}$ for some insulated gate transistors. These short-edge drive pulses introduce various issues,

causing motor damage and high-frequency drive signal overvoltage. Particularly when long transmission cables are used between motor and driver, strong voltage reflection occurs at the motor terminal due to distributed inductance and capacitance, doubling the dv/dt at the driver end and exacerbating hazards. This creates a series of negative effects and serious Electromagnetic Interference (EMI) and Electromagnetic Compatibility (EMC) problems. Research indicates that EMI levels generated by PWM AC speed control systems significantly exceed limits specified in relevant EMC standards [1,3,8,12].

In the absorption sphere shutdown drive mechanism cabinet project, the connection cable between driver and stepper motor measures 50 meters. The measured output voltage waveform from the stepper motor driver is shown in the left panel of Figure 3 [Figure 3: see original paper], with an output voltage range of -651V to 611V and a peak-to-peak value reaching 1260V. In contrast, when the connection cable is only 2.5 meters long, the output voltage range is -338V to 336V, as shown in the right panel of Figure 3, demonstrating that long-distance transmission between motor and driver significantly intensifies EMC problems [3,7]. Such high peak-to-peak PWM waves, particularly at high frequencies, severely pollute the power supply and grounding systems, substantially impacting surrounding equipment.

Interference Propagation Analysis

It can be determined that the working loop formed by the driver, stepper motor, and power cable constitutes a major interference propagation path in the absorption sphere shutdown drive mechanism cabinet. Interference transmission occurs through two primary mechanisms: conducted emission and radiated emission. Radiated emission involves electric and magnetic field radiation transmitted through space, while conducted emission directly interferes with external equipment through driver power lines, ground wires, and signal lines.

Radiated Emission

In this project, oscilloscope measurements revealed that altering the spatial position of interference sources (stepper motor, driver) produced virtually no change in interference signal waveforms, indicating that radiated emission is not the primary transmission path. This mechanism is therefore not discussed in detail herein.

Conducted Emission

In this project, the pulse generation equipment and stepper motor driver share the same upstream power supply system and grounding system, creating coupling circuits between them. Analysis of the coupling relationship between interference sources and external equipment, as illustrated in Figure 4 [Figure 4: see original paper], identifies four primary transmission pathways.

Due to distributed capacitance in signal lines and parasitic capacitance within the stepper motor, PWM modulation generates charging and discharging processes that form leakage currents, which flow into ground wires and pollute the grounding system. Under high-frequency dv/dt conditions, leakage currents return to the system power supply through ground lines, generating high-frequency Electromagnetic Interference (EMI). High-order harmonic currents create harmonic voltage drops across line impedance, interfering with weak electrical control signals in the system.

Introduction via Switching Power Supply The DCS system pulse generator features a floating ground design, insulated from earth, which theoretically isolates it from AC ground network interference. However, its upstream switching power supply incorporates Y capacitors for electrostatic protection, creating a coupling relationship with ground. When the system is severely polluted by leakage currents generated by PWM modulation, interference signals can enter the signal circuit through Path 4 described in Section 3.2 via the switching power supply's Y capacitors.

Concurrently, high-order harmonic currents produced by PWM modulation create harmonic voltage drops across line impedance, with resulting active and reactive power losses affecting power grid quality. Since the DCS system and stepper motor driver reside on the same power grid, interference can also be introduced through Path 2 via the switching power supply's L/N input terminals, with this influence transferred from the primary to secondary side through the power supply. The interference mechanism is illustrated in Figure 5 [Figure 5: see original paper], showing from left to right the 24V switching power supply, pulse generator, and stepper motor driver. Whether introduced through power supply L/N input terminals or Y capacitors, interference signals superimpose onto the pulse generator's output signals, becoming series-mode interference transmitted to the stepper motor driver.

Generally, larger switching power supply capacity corresponds to larger Y capacitors and stray capacitance, resulting in weaker resistance to PWM-generated interference. Measured interference amplitudes superimposed by switching power supplies of different capacities in this project are presented in Table 1 .

Introduction via Cable Shielding When the grounding system is polluted, the shielding layer of signal cables—being grounded—allows interference signals to enter the signal loop through the cable's distributed capacitance from the shield layer (Wire Shield). The mechanism is illustrated in Figure 6 [Figure 6: see original paper], showing how interference signals can enter the signal circuit through Path 4 described in Section 3.2 via the signal cable's shielding layer and distributed capacitance, becoming series-mode interference transmitted to the stepper motor driver.

Generally, longer signal cables exhibit larger equivalent distributed capacitance, resulting in weaker resistance to PWM-generated interference. Measured in-

interference amplitudes superimposed by cables of different lengths are shown in Table 2 .

Impact Analysis of Interference on Control Circuits

The driver acquires pulse signals through a photoelectric coupler (Photoelectric Coupler 2). The acquisition loop current I_1 represents the primary-side current of the coupler, which is transferred to the secondary-side current I_2 through the photoelectric coupler. This secondary current is then converted to secondary voltage V_{out} and transformed into standard digital logic levels “0” and “1” through Transistor-Transistor Logic (TTL) circuitry.

When the DCS pulse signal is a standard square wave, the photoelectric coupler (Photoelectric Coupler 1) conducts during high-level periods and cuts off during low-level periods. As the photoelectric coupler transitions from conduction to cutoff, I_1 correspondingly changes from conduction to cutoff, I_2 follows suit, and V_{out} transitions from low to high level, registering the acquisition of one pulse signal and converting it to one step angle of the stepper motor. The working principle diagram is shown in Figure 7 [Figure 7: see original paper].

During each high-level pulse width period, if significant interference is superimposed such that the equivalent voltage enters the low-level range, the photoelectric coupler may transition from conduction to cutoff, misinterpreting this as a pulse acquisition and causing the stepper motor to advance an extra step angle. The left panel of Figure 8 [Figure 8: see original paper] shows the oscilloscope-measured waveform without interference, while the right panel displays the waveform with substantial superimposed interference, where both high and low levels are overlaid with large-amplitude interference signals.

During each low-level pulse width period, the photoelectric coupler (Photoelectric Coupler 1) in the DCS signal generation equipment remains in cutoff state, preventing current loop formation. Consequently, interference signals generally do not affect operation or cause the stepper motor to rotate incorrectly. However, under extreme conditions—excessive interference amplitude, overly long signal cables, large cable distributed capacitance, or excessively high interference frequency—a current loop may still form, as illustrated in Figure 9 [Figure 9: see original paper].

Interference Suppression Methods

Analysis above indicates that the primary interference in the absorption sphere shutdown drive mechanism cabinet is series-mode interference superimposed on the signal loop. Since series-mode interference signals are already overlaid onto normal measured signals and share the same status, their detrimental effects are difficult to eliminate. The most effective approach is to block the transmission paths.

Filter Design

Filter Design at Driver Upstream The high-temperature reactor absorption sphere shutdown drive mechanism cabinet project identified the interference spectrum through experimental data and designed highly matched dedicated filters. Appropriate filters were installed at the main power circuit of the cabinet and the entrance of each driver' s branch circuit, providing multiple layers of protection to reduce interference impact on the external power grid [9,10,13]. As shown in Figure 10 [Figure 10: see original paper], on transmission path 1, interference generated by the driver under PWM operating principles is substantially filtered under the action of various parameter filters, significantly reducing impact on the pulse generator and achieving anti-interference objectives.

EMC test verification demonstrated that without upstream filters and with 220VAC cabinet power supply, conducted emission (CE) test interference reached a peak-to-peak value of 100 dB V in the 100 kHz-500 kHz frequency band, far exceeding the 79 dB V limit specified in IEC61000-6-4. After implementing multi-stage filters upstream of the driver under identical test conditions, CE test interference decreased to 68 dB V, falling within normal specification ranges and substantially reducing external interference output.

Dedicated DT/DV Reactor Design at Driver Downstream Theoretical analysis indicates that adding DT/DV reactors between the driver and stepper motor, as shown in Figure 11 [Figure 11: see original paper], can effectively reduce PWM output peak values and thereby decrease external interference levels.

By measuring the motor terminal response spectrum and analyzing circuit characteristics and curve features, dedicated DT/DV reactors highly matched to this project' s application were designed. Before adding the dedicated DT/DV reactors, the measured output voltage range was -523V to 531V. After reactor installation, the range became -378V to 362V, with peak voltage decreasing from 1054V to 740V, as demonstrated in Figures 12 [Figure 12: see original paper] and 13 [Figure 13: see original paper].

Cable Selection Optimization

Reducing the conductor cross-sectional area of signal cables from the DCS cabinet to the driver and increasing cable twisting density can reduce interference voltage amplitude to 1/100 of its original value. Actual testing demonstrates that replacing ordinary twisted pair signal cables with Category 6 shielded twisted pair cables featuring smaller cross-sections and tighter twist pitches reduces interference impact on the stepper motor by nearly 100 times. Measurements show that using ordinary twisted pair cables results in motor rotation angle deviations of approximately 200°, whereas Category 6 shielded twisted pair cables reduce deviations to only about 2°. Experimental statistical data are presented in Table 3 .

Reasonable Wiring

During cabinet wiring, signal lines and power lines should be separated as much as possible to reduce mutual magnetic field interference. Signal and power cables must not be installed in parallel but should instead be routed through different conduit holes. Low-level signal lines should connect to adjacent signal terminals using the shortest possible conductors, and using the same cable for both power and signal lines is strictly prohibited. Ground wires with larger cross-sectional areas and minimal length should be utilized.

Through comprehensive measures including filter design, DT/DV reactor installation, optimized wiring, and proper grounding, the impact of the driver's PWM modulation mechanism on weak electrical signals transmitted over long distances under specific constraints has been effectively resolved. These measures successfully suppress system interference, reducing stepper motor operation angle deviation from $30^\circ/3600^\circ$ to $1^\circ/7200^\circ$, ensuring stable motor operation. This effectively prevents the possibility of erroneous or failed sphere dropping during long-term operation and periodic testing of the high-temperature reactor absorption sphere shutdown device, thereby enhancing nuclear safety levels.

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Author Contributions Statement

Li Chunguang: Responsible for conceptualizing and designing experiments, conducting research, performing statistical data analysis, and drafting the article.

Deng Xigang: Responsible for driver cabinet design and experimental data acquisition.

Gao Jingbin: Responsible for discussion of driver cabinet design schemes.

Song Xianjun: Responsible for discussion of driver cabinet design schemes.

Su Yu: Responsible for driver cabinet scheme design for the 600MW high-temperature reactor project.

Zhao Dawei: Responsible for driver research and development for the 600MW high-temperature reactor project.

Zhang Bo: Responsible for driver R&D and driver cabinet design for the 600MW high-temperature reactor project.

Li Tianjin: Responsible for process requirements and participation in experimental scheme verification testing.

Yu Hui: Responsible for driver cabinet design schemes and participation in scheme verification testing.

Yan He: Responsible for anti-interference design concepts for the driver.

Diao Xingzhong: Responsible for discussion of anti-interference design schemes for the driver cabinet.

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