1st IGALL meeting phase 8 Action Item 0.5 and 2.27

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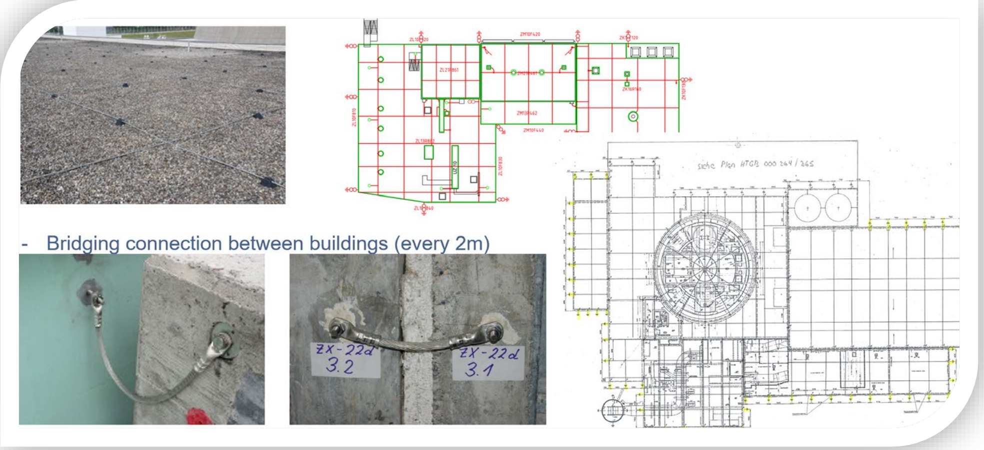
How Lightning Impacts stress NPP Equipment

Transformers (Generator Step-Up, Auxiliary, Startup Transformers)

Key impacts

- **Insulation degradation**
  - High-frequency surges from lightning stress the winding insulation. Aging insulation becomes brittle, making it more vulnerable to partial discharge and eventual failure.
- **Overvoltage stress on bushings**
- Bushings are often the weakest point. Repeated lightning impulses accelerate:
  - moisture ingress
  - thermal cracking
  - dielectric breakdown
- **Winding deformation**
  - Very steep-front surges can cause mechanical forces that distort windings, especially in older units.
- **Oil degradation**
  - Surges can create localized heating, accelerating oil oxidation and sludge formation.



Lightning Arresters (Surge Arresters)

- Lightning arresters are designed to absorb lightning energy, but the effects of aging reduces their effectiveness.
- **Active degradation Mechanis**
  - **Thermal aging of metal-oxide varistors (MOVs**
  - **Moisture ingress**
  - **Corrosion**
- **Degradation Effect**
  - **Reduced energy-handling capability (higher currents, temperature, electrical stress in affected equipment)**
  - **Long-term effect**

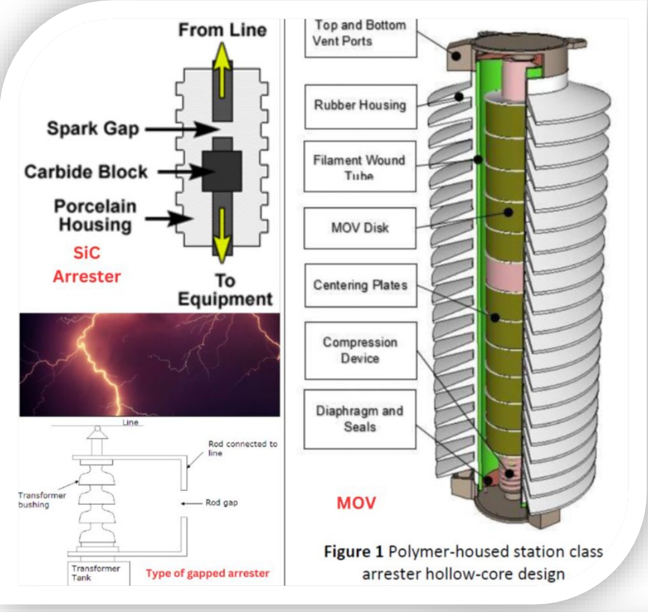


Figure 1 Polymer-housed station class arrester hollow-core design

Switchyard Equipment (Breakers, Disconnects, Buswork, Insulators)

Impact of Lightning surges can:

- **Circuit breakers**
  - erode contacts
  - stress interrupter chambers
  - cause mechanical shock to operating mechanisms
- **Disconnect switches**
  - flashover across open gaps
  - pitting of contact surfaces
  - accelerated corrosion
- **Insulators (porcelain or composite)**
  - surface tracking
  - puncture of aged porcelain
  - erosion of polymer insulators
  - contamination flashover (especially in coastal or industrial areas
- **Buswork**
  - thermal expansion
  - mechanical vibration
  - stress at joints and clamps
- **Long-term effect**
  - Switchyard reliability decreases, increasing the chance of forced outages.

Why Aged Equipment Is More Vulnerable?

- **Aged equipment has:**
  - Weakened insulation
  - Reduced dielectric strength
  - Accumulated moisture
  - Corroded connections
  - Degraded protective devices

- **This means a lightning impulse that a new system would survive may cause:**
  - Flashover
  - Insulation failure
  - Transformer damage
  - Breaker misoperation

How Nuclear Plants Mitigate Lightning Impact

Nuclear plants typically use:

- High-performance surge arresters
- Shield wires and grounding grids
- Transformer impulse testing
- Periodic arrester leakage-current monitoring
- Infrared inspections for loose or heated connections
- Condition-based maintenance (DGA, PD monitoring, bushing power factor tests)

These measures **significantly reduce risk**, but aging equipment still requires more frequent monitoring.

Impact of Lightning Strikes on an Aged Grounding System

Increased Ground Resistance

- Over time, grounding systems degrade due to:
  - corrosion of buried conductors
  - drying or compacting of soil
  - broken or disconnected ground bonds
  - deterioration of ground rods

When resistance increases, lightning energy cannot disperse quickly. This leads to:

- higher ground potential rise (GPR)
- greater voltage stress on equipment
- increased risk of flashover in the switchyard

Aging = slower dissipation of lightning energy = higher transient voltages everywhere.

Higher Ground Potential Rise (GPR)

- A lightning strike injects tens of thousands of amps into the ground grid. If the grid is degraded, GPR can spike dramatically.
- Consequences:
  - step and touch potentials exceed safe limits
  - control cables and relay panels experience induced surges
  - transformer neutrals see elevated voltages
  - Protective relays may misoperate
- In a nuclear plant, this can cause nuisance trips or unexpected breaker operations.

Increased Stress on Transformers and Switchyard Equipment

- When the grounding system is weak, lightning energy finds alternative paths through:
  - transformer windings
  - bushing insulation
  - surge arresters
  - breaker frames
  - control wiring

- This accelerates the aging of:
  - transformer insulation
  - breaker interrupter chambers
  - bushing dielectric materials
  - surge arrester MOV blocks
  - Older equipment is already closer to its dielectric limits, so lightning-induced stress can push it over the edge.

Safety Risks for Personnel

- Higher GPR and degraded grounding increase:
  - step potential hazards
  - touch potential hazards
  - risk of arc flash during lightning events

- Aging grids can turn a normally safe switchyard into a hazardous zone during storms.

Induced Surges in Control and Protection Systems

- **Aged grounding grids often have:**
  - Broken bonds between the switchyard and control building
  - Deteriorated cable shields
  - Corroded grounding bars
- **This allows lightning-induced currents to enter:**
  - relay panels
  - SCADA systems
  - communication circuits
  - turbine and reactor control systems
- **Even if the nuclear island is isolated, the electrical noise can cause:**
  - false relay operations
  - spurious alarms
  - loss of communication links

Why Aging Makes Everything Worse

- **A new grounding system:**
  - Has low resistance
  - Has strong mechanical bonds
  - Disperses lightning energy quickly
- **An aging system:**
  - Has higher resistance
  - Has corroded or broken conductors
  - Forces lightning energy into equipment instead of the soil
- Lightning doesn't change—but the system's ability to handle it does.

Research Objectives 3002029459

- To understand the impact of recent lightning events at NPP Switchyards.
  - Voltage surge
  - Ground potential jump
  - Identify contributors to failure
  - Limit effects on equipment
- Review industry data from NOAA & other weather Authorities.
- Obtain actual plant data from lightning events.
- Assess conditions of lightning and grounding at selected NPPs.
  - Ground grid design adequacy
  - Lightning protection system design
  - Review and update maintenance practices
  - Emphasize defense-in-depth
- Recommend steps to improve.

System	Direct Strike	Near Strike	Distant Strike
Structure	Mechanical and thermal stress with voltage rise	Little effect	No effect
Overhead Ground	Mechanical and thermal stress with voltage rise and conduction of lightning current	Some voltage surge	Little effect
Phase Conductor	Mechanical and thermal stress with voltage surge propagation and transient current	Some voltage surge depending on whether back flashover has occurred	Little effect although a surge can propagate as a traveling wave
Ground Mat	Voltage rise of earth ground	Voltage rise of earth ground	Little effect
Surge Arresters	Engagement by rate of rise or excessive voltage possible overcurrent condition	Engagement by rate of rise or excessive voltage	Possible engagement
Circuit Breakers	Transient high voltage and high current with possible thermal stress	Transient high voltage and high current with possible thermal stress	Possible engagement depending on conditions of the distant strike
Transformers	High voltage exceeding insulation ratings with high currents and thermal stress	Possible high voltage surge	Likely only affected if breakers or other components fail
Switchyard Instruments	Stress by high transient voltages and currents. Possible arc over.	Stress by high transient voltages and currents	Little effect
Plant Equipment	Surge voltages depending on intensity of lightning strike and available upstream protection	Affected by tripping of switchyard breakers	Affected by tripping of switchyard breakers
Plant Instrumentation	Magnetic or capacitive coupling resulting in circuit failure of false signals	Magnetic or capacitive coupling resulting in circuit failure of false signals	Little effect

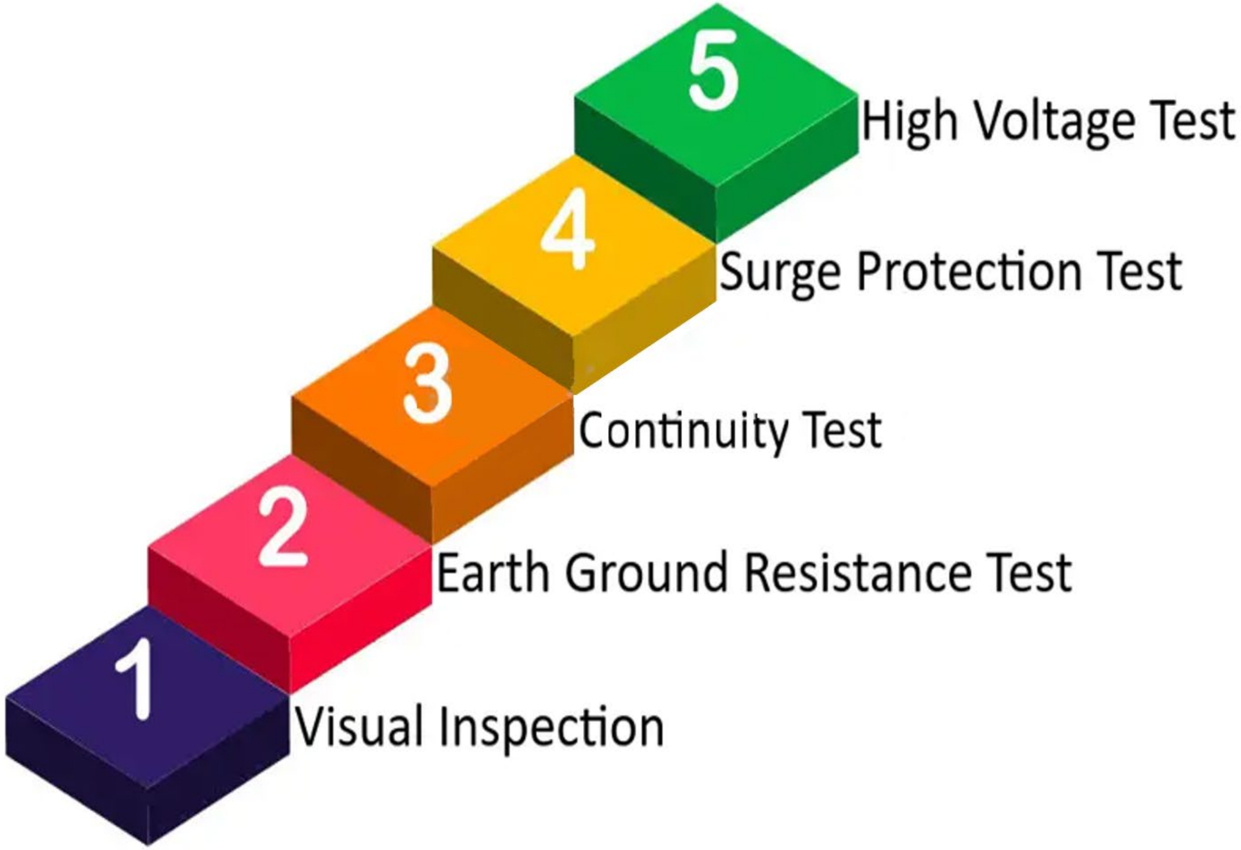
Global NPPs Stations Located in High Lightning Density Regions

- Examining Lightning Protection Strategies Worldwide at NPPs

Top Tier Lightning Risk	Second Tier Lightning Risk	Third Tier Lightning Risk
Turkey Point 3, 4	Grand Gulf 1	Arkansas Nuclear 1. 2
Saint Lucie 1, 2	Farley 1, 2	Browns Ferry 1, 2
Waterford 3	Hatch 1, 2	Oconee 1, 2, 3
South Texas 1, 2		Vogtle 1, 2
River Bend 1		Summer
		Sequoyah 1, 2
		Watts Bar 1, 2

Top Tier Lightning Risk	Second Tier Lightning Risk	Third Tier Lightning Risk
Embalse Unit 1, Argentina	Taishan Units 1 and 2, China	Onagawa Unit 1, Japan
Atucha Units 1 and 2, Argentina	Daya Bay Units 1 and 2, China	Tokai Unit 1, Japan
Angra Units 1, 2, and 3, Brazil	Ling Ao Units 1-4, China	Hamaoka Units 1 and 2, Japan
Koeberg Units 1 and 2, South Africa	Lufeng Unit 5, China	Paks Unit 1-4, Hungary
Kudankulam Units 1-6, India	Zhangzhou Units 1 and 2, China	Krsko Unit 1, Slovenia
Narora Units 1 and 2, India	Fuqing Units 1-6, China	
Rajasthan Units 1-8, India	Ningde Units 1-4, China	
Chasnupp Units 1-5, Pakistan	Sanmen Units 1-4, China	
Kakrapar Units 1, 2, and 4, India	Fangjiashan Units 1 and 2, China	
Changjiang Units 1-4, China	Qinshan Units 1-3, China	
Fangchenggang Units 1-4, China	Tianwan Units 1-8, China	
Yangjiang Units 1-6, China	Maanshan Units 1 and 2, Taiwan	
	Kuosheng Unit 2, Taiwan	

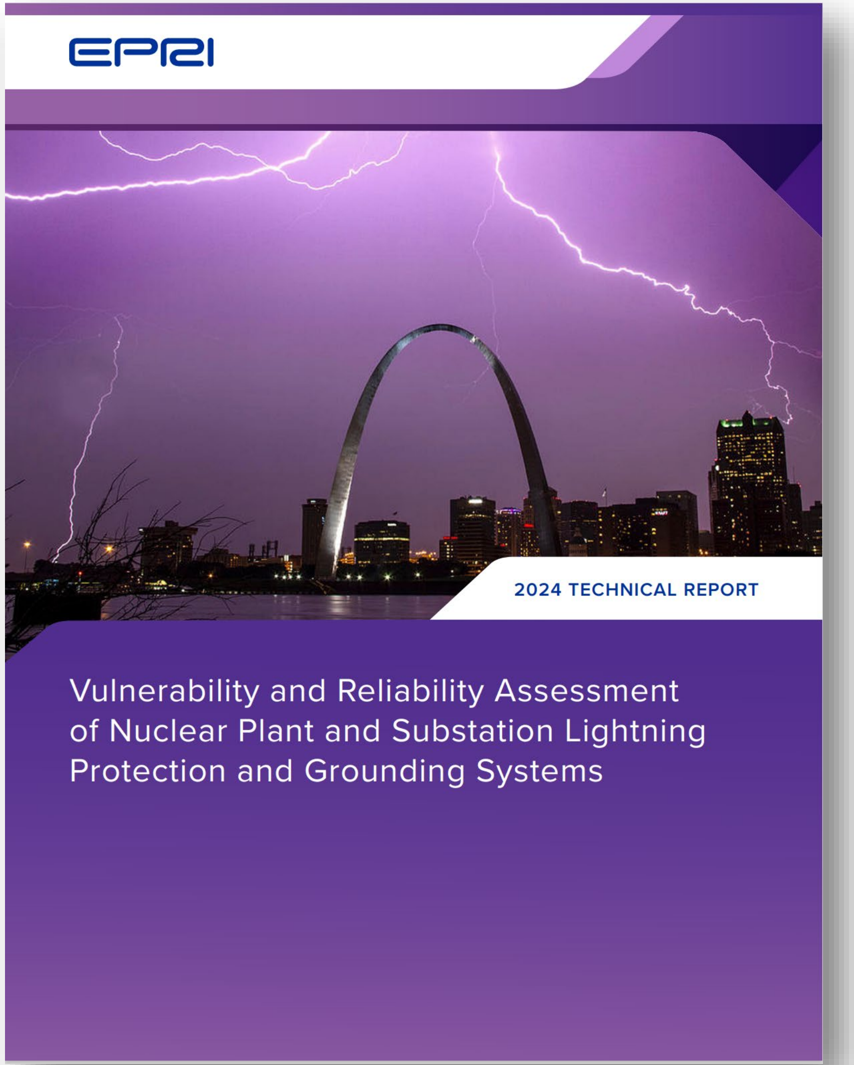
Testing Your Lightning Protection System



Lightning Protection Improvement Opportunity

Summary of Lightning Protection & Grounding Study

- **The lightning protection and grounding report was published in 2024.**
- **Initial Findings**
  - Aging Equipment
  - Lack of Maintenance
- **Major Recommendations are**
  - Periodic site inspections
    - ✓ Visual inspection
    - ✓ Walkdown
  - Maintenance and Testing
  - Additional site inspections
    - ✓ Provide insights LPS and grounding designs.
    - ✓ Provide insights based on regional differences.
    - ✓ Provide insights into inspection and maintenance practices.
  - Identified potential improvements to LPS inspections.
    - ✓ The Potential value for developing a software tool for inspection, to evaluate risk and revenue. exposure of deficiencies, and to track and trend key indicators of design adequacy.
    - ✓ Value added from outside subject matter experts when performing LPS and Grounding evaluations.



Conclusion for Action Item 0.5
Impact of environmental conditions in NPPs resilience.

- Include extreme temperature rise in plant equipment.
- Lighting strike as a stressor in Electrical and I&C.
- Integrity of grounding system.

Conclusion for Action Item 2.27

- Search in existing AMPs for including lighting as a stressor.
- Develop an AMP for grounding

Reduced Effectiveness of Lightning Arresters

- **Arresters rely on a low-impedance path to ground.** If the grounding system is degraded:
  - Arrester discharge voltage increases
  - Residual voltage passed to the equipment rises
  - Arresters overheat more easily
  - Arrester failure becomes more likely

- An arrester on a poor ground grid can't protect the transformer behind it.

What Nuclear Plants Typically Do to Mitigate

- Most plants use:
  - Periodic ground grid resistance testing
  - Fall-of-potential measurements
  - Thermography for loose ground connections
  - Soil resistivity surveys
  - Ground grid mapping with injection testing
  - Replacement of corroded ground rods and conductors
  - Bonding upgrades between the switchyard and the control building
- These steps restore the grounding system's ability to safely dissipate lightning energy.

Assessment of Lightning Protection & Grounding

- Lack of Maintenance Contributes to LPS-Related Failures
- Site Inspections Identified LPS and grounding Issues
- Impact of Lightning Strike On Nuclear Switchyard
- NPPs LPS Inspection, Maintenance Strategies & Testing
- Ground Grid Maintenance and Testing Strategies
- Strike Warning Technology
- Human Performance Contributors to LPS Failures
- Considerations for LPS Improvement