What Happens Before the Hotspot? UV and Thermal Imaging in High-Voltage Systems

Different Failure Mechanisms. Complementary Detection Technologies.

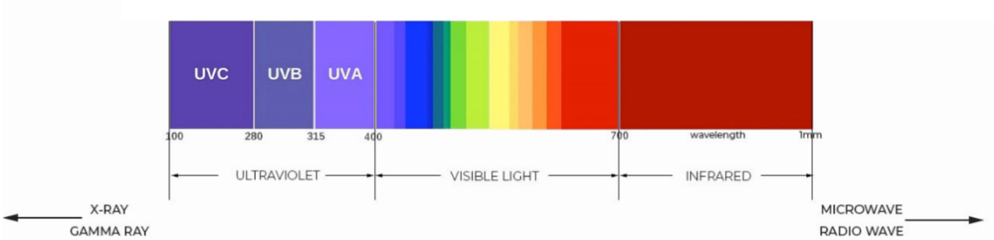
Electrical failures in high-voltage systems rarely originate from a single cause. Some begin with excessive electric field stress. Others develop due to resistive heating associated with current flow. Mechanical damage, improper installation, material aging, contamination, and environmental exposure often create the conditions that trigger or accelerate these electrical degradation processes. Although these mechanisms may ultimately result in flashover, outage, or equipment damage, they represent fundamentally different pathways of deterioration.

Ultraviolet (UV) and Thermal (Infrared, IR) imaging technologies are designed to detect these different physical phenomena. UV imaging visualizes voltage-related discharge activity such as corona partial discharge and surface tracking. Thermal imaging identifies temperature rise associated with current flow and resistive losses. Because each technology responds to a different trigger, they reveal different dimensions of equipment condition.

In many situations, voltage stress and corona activity are present before measurable heating develops. This means that UV inspection can, in certain cases, provide earlier visibility into developing defects that are not yet detectable through thermal imaging.

RGB visual inspection adds contextual information by documenting physical damage, mechanical defects, installation irregularities, and contamination. While RGB does not measure electrical stress or heat directly, it supports interpretation and reporting within a comprehensive inspection workflow.

Understanding how these technologies align with different failure mechanisms is essential for designing an inspection strategy that captures both early-stage electrical stress and later-stage thermal degradation.

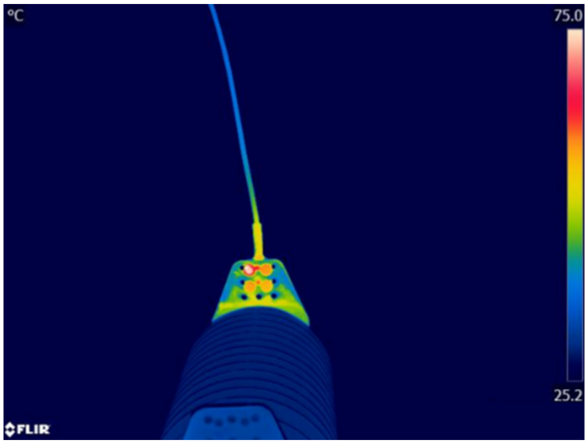


Position of Ultraviolet, Visible, and Infrared Regions in the Electromagnetic Spectrum

1. Thermal Imaging and the Physics of Heat-Related Electrical Faults

1.1 Infrared Radiation in the Electromagnetic Spectrum

Thermal cameras operate in the infrared region of the electromagnetic spectrum. Most inspection systems detect radiation in the long-wave infrared band, typically between 7 and 14 micrometers. This region lies beyond visible light and is associated with thermal emission.



Thermal hotspot identified at a loose bolted connection

All objects above absolute zero emit electromagnetic radiation as a function of temperature. In electrical equipment, this radiation increases when localized heating occurs. Thermal cameras measure this emitted energy and convert it into a temperature-mapped image.

1.2 How Thermal Anomalies Form in Electrical Systems

Thermal anomalies in electrical infrastructure arise when electrical energy is unintentionally converted into heat. This typically occurs when resistance increases at a conductive interface or within a component operating under load.

Common causes include:

- Loose or improperly torqued connections
- Degraded compression joints
- Overloaded components
- Phase imbalance
- Internal component deterioration

When current flows through an area of elevated resistance, localized heating develops. If the temperature of that region rises measurably above similar components operating under comparable conditions, the thermal camera detects the differential and displays it as a hotspot.

A critical aspect of thermal diagnostics is that heat generation depends on current magnitude. Without sufficient load, even a defective connection may not produce a detectable temperature rise. For this reason, thermal inspection effectiveness is directly tied to operating conditions.

In many cases, measurable temperature rise appears after resistance has already increased significantly. Thermal imaging is therefore particularly effective at identifying faults that have progressed to a stage where energy loss is occurring in the form of heat.

Thermal cameras do not measure voltage stress or electric field concentration. They detect emitted infrared radiation associated with surface temperature. The anomaly observed is the thermal consequence of electrical inefficiency, not the underlying electric field behavior itself.

1.3 Recommended Inspection Conditions for Reliable Thermal Measurement

Accurate interpretation of thermal anomalies depends not only on camera capability, but also on inspection conditions. Industry guidance, including EPRI thermography practices for transmission and substation systems, emphasizes that thermal measurements must be performed under controlled and well-documented operating conditions.

For meaningful results, line loading should typically be at least 40% of the rated maximum electrical load. Temperature rise associated with resistive defects is directly influenced by current magnitude. Inspections conducted under light load may not reveal developing problems, even if elevated resistance is present.

Thermal performance should be evaluated comparatively. Rather than relying on absolute temperature alone, inspectors are advised to compare the thermal signature of similar components operating under similar load and environmental conditions. Relative differences often provide more reliable interpretation than standalone measurements.

Environmental effects must also be considered. Wind introduces forced convective cooling, which can suppress apparent temperature rise and reduce the visibility of developing hotspots. Limiting inspections to low-wind conditions improves consistency and repeatability.

Solar radiation can significantly influence surface temperatures, particularly on metallic or low-emissivity components. Direct sunlight may create apparent hotspots unrelated to electrical stress. For this reason, inspections are preferably conducted under overcast conditions, or during early morning and evening hours when solar loading is minimized.

Ambient temperature should be recorded as part of the inspection dataset. Temperature rise above ambient is often more diagnostically meaningful than absolute surface temperature alone.

Finally, thermal imagery must be captured under proper line-of-sight conditions, with correct focus, distance, temperature range, and scaling. Improper imaging parameters can distort apparent thermal gradients and reduce diagnostic accuracy.

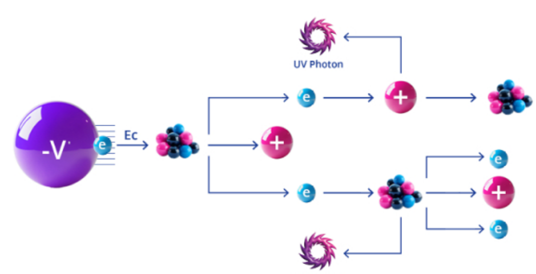
Substation inspection with a thermal camera

2. Ultraviolet (UV) Imaging and the Physics of Voltage-Related Electrical Faults

2.1 Electric Field Ionization, Partial Discharge and Ultraviolet Emission

Ultraviolet inspection is based on a fundamentally different physical mechanism than thermal imaging. Instead of measuring heat, UV systems detect light emitted during air ionization caused by high electric field intensity.

When the electric field surrounding an energized conductor exceeds the dielectric strength of air at localized regions, typically on the order of 2.4–3 kV per millimeter, the surrounding air molecules become ionized. This phenomenon, commonly referred to as corona partial discharge, results in the emission of electromagnetic radiation primarily in the ultraviolet range.

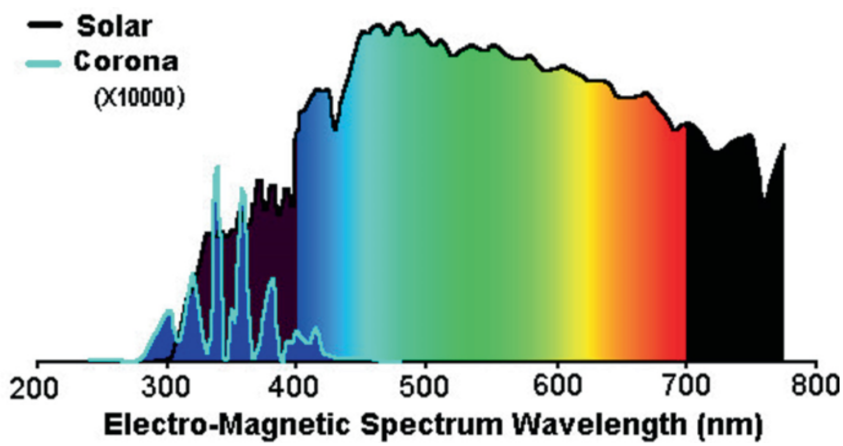


The ionization process

Unlike full electrical breakdown, partial discharge is localized and does not bridge the entire insulation gap. It involves small, repetitive ionization events rather than sustained current flow. Full discharge, by contrast, represents complete dielectric failure and is typically associated with arcing and rapid damage escalation.

Corona partial discharge light emission occurs broadly within the UVA (315-400 nm), UVB (280-315 nm), and UVC (100-280 nm) regions. However, sunlight also contains significant ultraviolet radiation within the UVA and UVB bands. This overlap presents a challenge for daytime PD detection, since solar ultraviolet radiation can overwhelm or mask corona PD signals.

To enable reliable daylight inspection, solar-blind UV cameras operate within the UVC band. In this region of the spectrum, atmospheric ozone absorbs solar radiation before it reaches the Earth's surface. As a result, the background solar UV level in the UVC range is extremely low, allowing corona discharge to be detected with high contrast even under full daylight conditions.

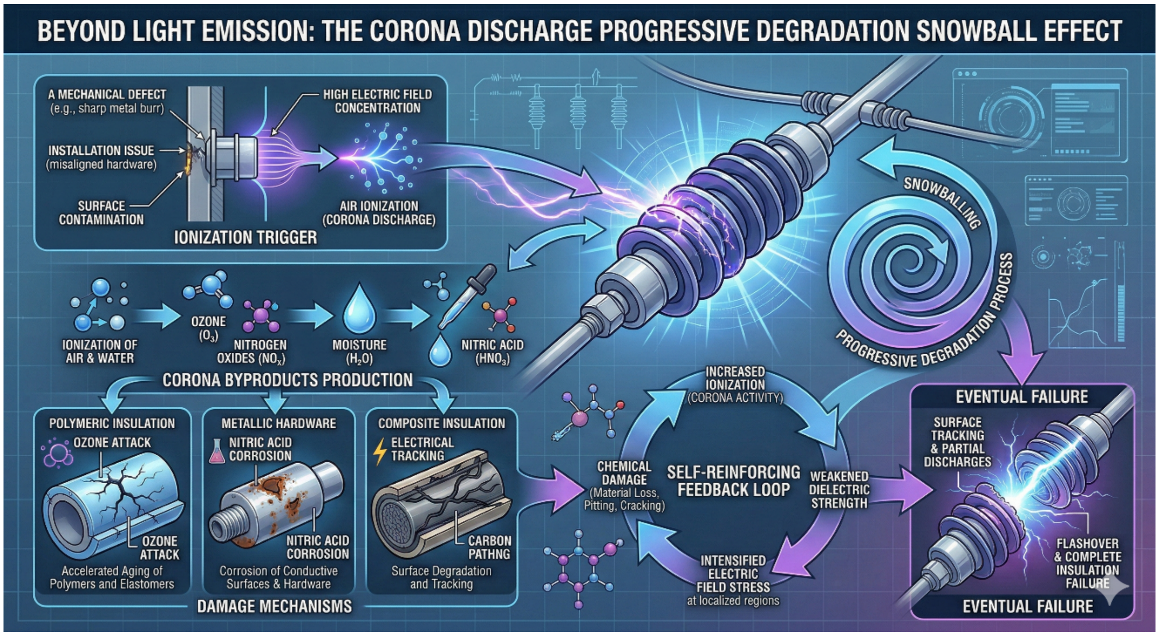


A spectral graph illustrates the distribution of corona emission and solar radiation across the ultraviolet spectrum, demonstrating why solar-blind filtering is required for reliable daytime inspection.

Beyond light emission, corona discharge produces chemical byproducts that directly contribute to material degradation. Ionization of air generates ozone and nitrogen oxides, which can combine with moisture to form nitric acid. These compounds attack surrounding materials.

Ozone accelerates aging of polymeric insulation and elastomeric components. Nitric acid promotes corrosion of metallic hardware and conductive surfaces. Over time, this chemical activity degrades insulation, increases surface conductivity, and reduces dielectric strength.

Corona therefore represents more than a visual phenomenon. It initiates a progressive degradation process. High electric field concentration due to a mechanical defect, installation issue or contamination leads to ionization. Ionization produces chemical damage. Chemical damage further weakens materials and can intensify electric field stress at localized regions. The process can become self-reinforcing, gradually evolving from discharge activity into surface tracking, flashover, and eventual failure.



The corona discharge snowball effect

2.2 How Voltage-Driven Anomalies Form in Electrical Systems

Corona partial discharge does not originate in isolation. It is a direct consequence of non-uniform electric field distribution within energized equipment. High-voltage components are designed to control and distribute electric stress evenly. When that distribution is disturbed, localized field intensification can occur.

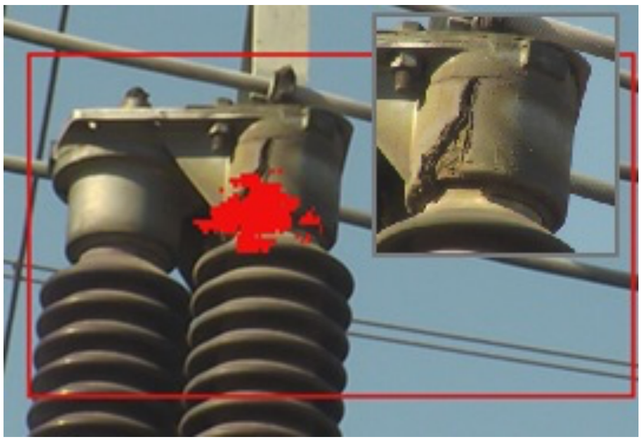
In practical systems, electric field concentration commonly develops due to:

- Mechanical damage, such as cracked insulators or broken conductor strands
- Improper installation, loose components or incorrect hardware geometry
- Surface contamination from salt, dust, or industrial pollution
- Loss of hydrophobic properties in polymer insulators
- Erosion of insulating cement in porcelain insulators
- Absence or improper placement of corona rings
- Corroded end fittings and metallic accessories
- Bird-cage deformation of stranded conductors

- Sharp edges or improper conductor spacing

Each of these conditions alters the intended electric field profile. Even minor geometric irregularities can significantly increase local field intensity.

When field strength becomes sufficiently concentrated, air ionization begins at those specific locations. The resulting corona partial discharge is detectable using solar blind UV imaging and serves as a direct indicator of abnormal voltage stress.



Corona discharge activity on HV insulator detected using a UV camera

2.3 Recommended Inspection Conditions for Reliable UV Detection

Accurate ultraviolet inspection depends on understanding the environmental and electrical conditions that influence corona visibility. Unlike thermal measurements, which are strongly dependent on load current, corona activity is governed primarily by electric field intensity.

Corona can be present even under no-load or light-load conditions. Because it is driven by localized voltage stress rather than resistive heating, significant current flow is not required for discharge activity to occur.

Environmental factors also influence discharge behavior. Increased humidity can enhance corona visibility by lowering the breakdown strength of air and promoting ionization. For this reason, inspections conducted during periods of moderate to high humidity may reveal discharge activity more clearly than in very dry conditions.

As with all optical inspection methods, proper line-of-sight, focus, and distance are essential. Discharge intensity decreases with distance, and imaging parameters must be selected to ensure accurate representation of activity.

3. Electrical Failure Mechanisms and Diagnostic Visibility

Electrical degradation in high-voltage systems does not progress along a single path. Depending on the initiating condition, a defect may first manifest as abnormal electric field behavior, as resistive heating, or as a combination of both.

Electrical failure

Field-driven defects disturb the intended electric stress distribution of a component. These conditions may remain thermally invisible, particularly under light load, yet still indicate deteriorating insulation performance or geometric irregularities.

Resistive defects, by contrast, develop within the current-carrying path. Elevated resistance under load leads to localized heating that becomes detectable through infrared imaging. In these cases, the dominant symptom is energy dissipation in the form of heat rather than discharge activity.

As degradation progresses, mechanisms can overlap. A component experiencing prolonged discharge may eventually develop resistive tracking and begin to generate measurable heat. Conversely, a resistive defect may alter geometry or material condition in ways that intensify local electric field stress.

The key practical implication is that ultraviolet and thermal imaging do not compete. They provide visibility into different physical aspects of system behavior. In certain scenarios, corona discharge may be detectable before thermal rise develops. In others, heating may be the first observable indicator.

Effective diagnosis therefore depends on recognizing which physical mechanism is dominant at the time of inspection.

4. Practical Interpretation and Decision-Making

Understanding failure mechanisms is important. Interpreting what inspection findings actually mean in the field is equally critical. Ultraviolet and thermal imaging provide data, but proper decision-making depends on context, operating conditions, and correlation.

4.1 What UV Findings Usually Mean in the Field

The presence of corona discharge indicates localized electric field concentration. It does not automatically mean imminent failure, but it does signal abnormal electrical stress that warrants evaluation.

Interpreting UV findings requires considering:

- The type, material, and geometry of the component
- The exact location of the discharge
- System voltage level and the criticality of the asset
- Historical inspection data
- Observable visual indicators
- Environmental conditions such as humidity, contamination, and pollution level

For example, discharge at sharp hardware edges may reflect geometric field concentration. Discharge along an insulator surface may suggest mechanical defects, contamination or loss of hydrophobicity. Activity at end fittings may indicate corrosion or improper grading.

Severity should be evaluated qualitatively. A small but persistent discharge at a critical location may be more significant than a stronger discharge at a geometrically expected stress point. Guidelines like the EPRI guidelines or the Gridnostic software help interpret the results.

4.2 What Thermal Findings Usually Mean in the Field

Thermal anomalies represent measurable temperature rise relative to comparable components operating under similar conditions, or over ambient temperature. Interpretation should be based on relative comparison rather than absolute temperature alone.

Key considerations include:

- Comparison with adjacent phases or similar components
- Load magnitude at time of inspection
- Ambient temperature
- Surface emissivity characteristics

Small temperature rises require careful judgment. A minor delta under high load may be insignificant, while a similar delta under moderate load could indicate developing resistance.

Inspectors must also account for environmental influences. Solar reflections, low-emissivity metallic surfaces, and improper camera settings can produce misleading apparent hotspots. Evaluating viewing angle, focus, and measurement scale is essential for reliable interpretation.

Thermal findings generally indicate current-driven deterioration. They reflect energy loss in the form of heat and often correspond to resistive pathways within the current-carrying structure.

4.3 Why Correlation Matters

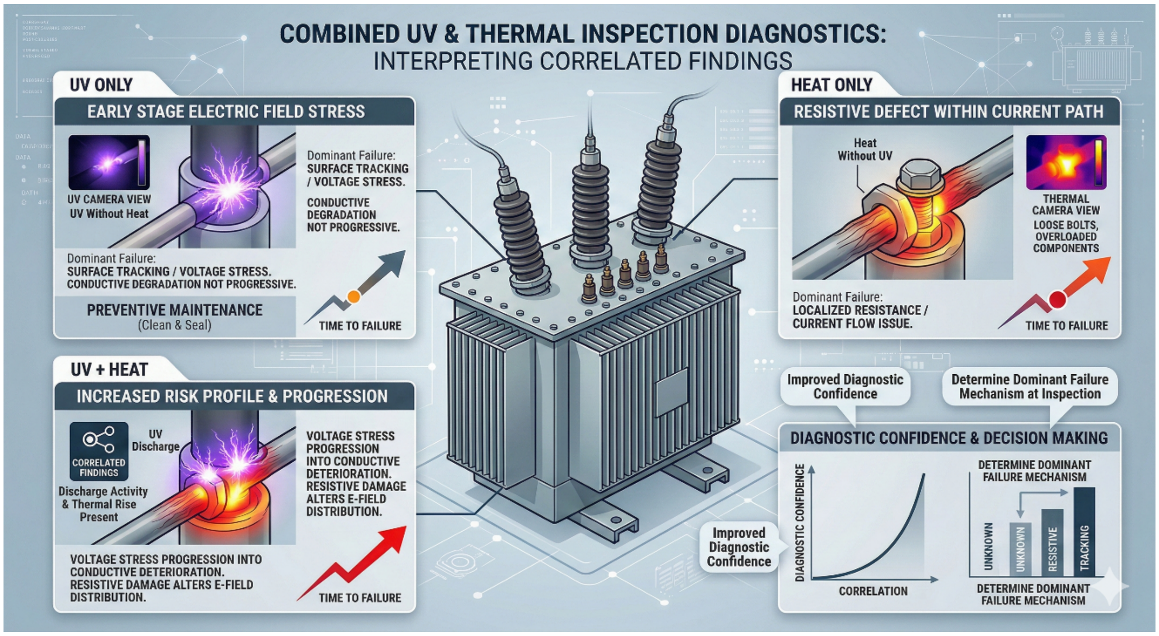
Ultraviolet and thermal findings must be interpreted together when available.

UV without heat often indicates early-stage electric field stress before conductive degradation has progressed. In such cases, preventive maintenance may prevent escalation.

Heat without UV typically indicates a primarily resistive defect within the current path. Examples include loose bolted connections or overloaded components.

When both discharge activity and thermal rise are present at the same location, the risk profile increases. This may indicate that voltage stress has progressed into conductive deterioration, or that resistive damage has altered electric field distribution.

Correlation improves diagnostic confidence and helps determine the dominant failure mechanism at the time of inspection.



Combined UV & Thermal inspection diagnostics

5. Field Examples: UV vs Thermal in Practice

5.1 Distribution Pole Inspection

A distribution pole was inspected using both ultraviolet and thermal imaging.

In the ultraviolet image (right), two distinct corona discharge locations were identified, visible as white emission spots. Both discharges were associated with insulators.

The first discharge was located at the live end of the insulator. This type of activity can occur at energized hardware interfaces where electric field concentration is expected. While it indicates localized stress, it may represent a geometrically induced condition rather than immediate insulation failure.

The second discharge was observed at the dead end of the insulator. This location is more critical because it is intended to isolate the energized conductor from the pole structure. Corona activity at the dead end suggests that the insulator may not be fully insulating as designed. In such cases, leakage current or surface degradation could allow voltage to couple toward the pole hardware. Persistent discharge at this location warrants immediate evaluation, as it may indicate compromised insulation performance and a potential safety risk if the structure becomes unintentionally energized.

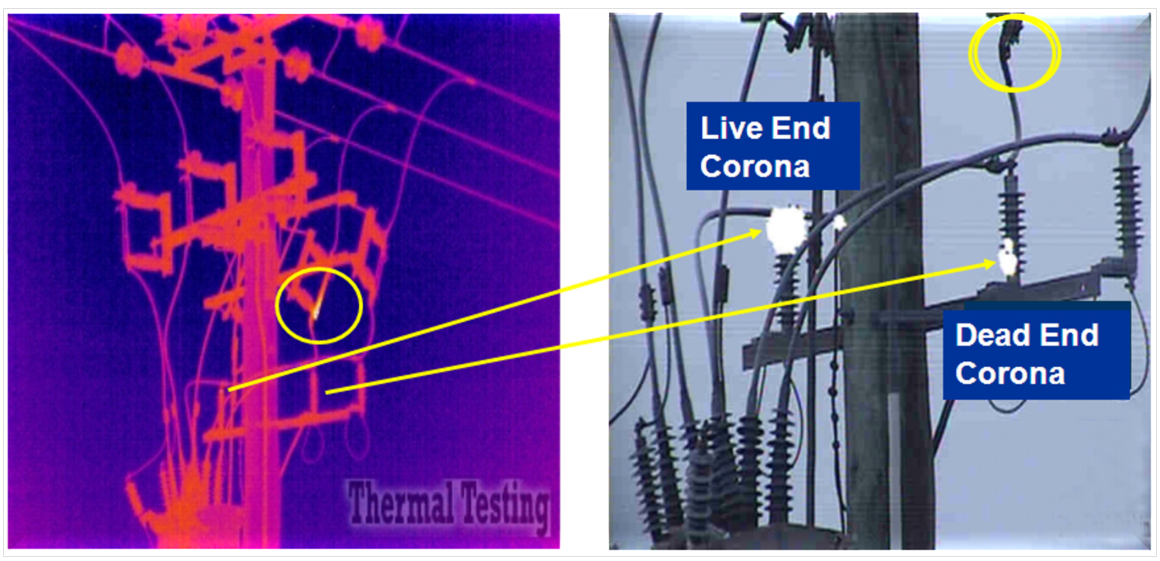
The corresponding thermal image (left) showed no measurable hotspot at either discharge location. This indicates that the detected corona activity was voltage-driven and had not yet progressed to a stage where resistive heating was present.

However, the thermal image revealed a separate hotspot at a compression connector (in circle). No ultraviolet discharge was observed at this connector location. The thermal anomaly suggests a resistive defect within the current-carrying path, likely caused by improper compression, mechanical loosening, or contact degradation.

This case illustrates two independent failure mechanisms occurring on the same structure:

- Voltage-driven corona activity on insulators, detectable by UV but not thermal
- Current-driven resistive heating at a connector, detectable by thermal but not UV

Together, these findings demonstrate how ultraviolet and thermal imaging provide complementary visibility into different aspects of system condition.



Multi-Spectral Inspection of a Distribution Pole Using UV and Thermal Cameras

5.2 Substation Inspection Using DJI M300 Drone

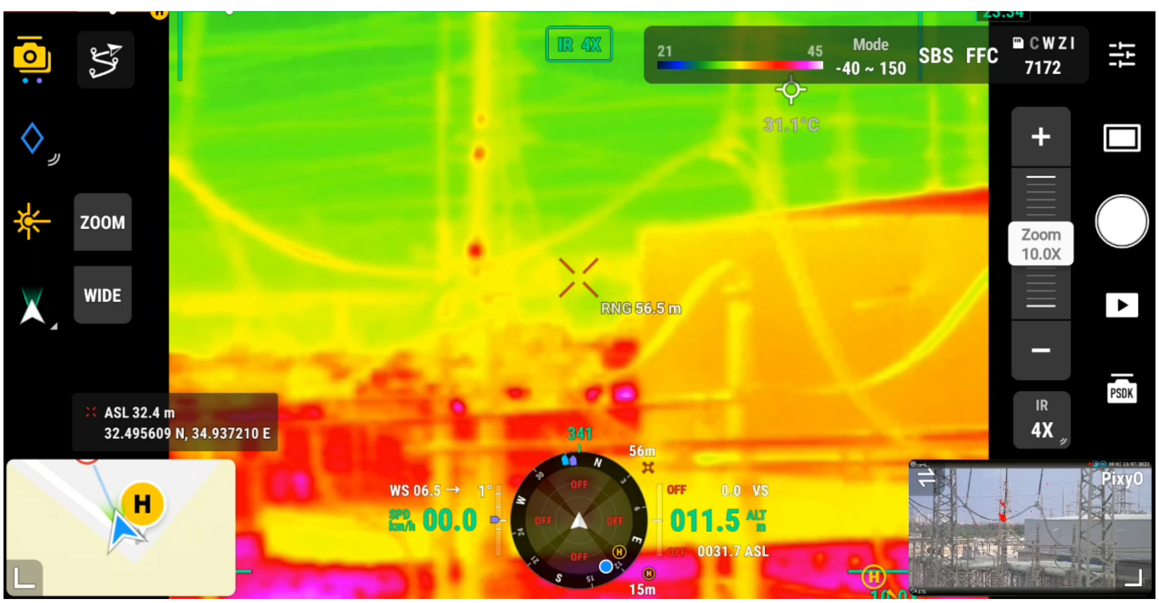
A substation was inspected using a DJI M300 drone equipped with both UV and thermal cameras operating simultaneously.

The image captured from the drone's remote controller shows two thermal hotspots on a high-voltage bushing, on the main display. On the lower right display, UV imaging reveals discharge activity at the same location, represented by red emission spots.

Simultaneous UV and IR Inspection on DJI M300

The thermal hotspots indicate localized temperature rise under load, suggesting resistive heating within or around the bushing assembly. The simultaneous presence of ultraviolet discharge at the same location confirms abnormal electric field behavior and active corona PD due to degradation of the insulation.

When both discharge activity and measurable heating are observed on a critical component such as a high-voltage bushing, the risk level increases significantly. This indicates that the defect is no longer purely voltage-driven or purely resistive, but involves overlapping degradation mechanisms.



Hotspots and corona discharges detected on a high voltage bushing

5.3 Ceramic Insulator Inspection

A ceramic insulator was inspected using RGB, thermal, and ultraviolet imaging.

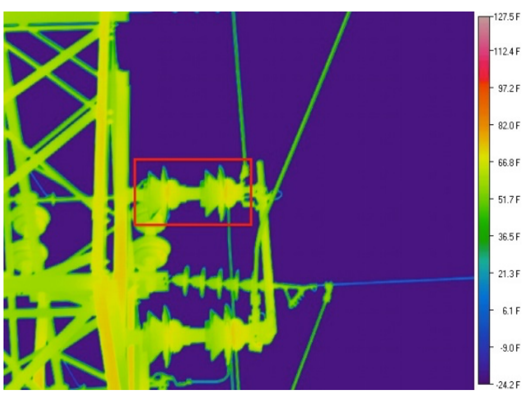
Visible (RGB) image of ceramic insulator

The RGB image showed no visible signs of mechanical damage, cracking, contamination, or structural irregularities. The thermal image also revealed no measurable temperature rise or abnormal heating along the insulator or its fittings under the prevailing load conditions.

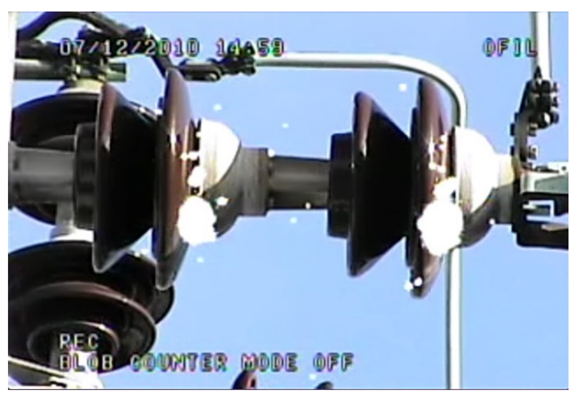
However, ultraviolet imaging identified discharge activity at two locations between the insulator disc and the metal cap. The discharge appeared concentrated at the interface region, suggesting localized electric field concentration.

Corona activity at the disc-to-cap interface may indicate the presence of a small air gap, improper seating during installation, cement degradation, or loss of internal bonding. Although no thermal anomaly was present, the discharge suggests compromised dielectric performance at that interface.

This case highlights a key diagnostic distinction: the defect was not mechanically visible and had not progressed to resistive heating. It was detectable only through ultraviolet imaging, indicating voltage-driven stress at an early stage.



Thermal image: no anomaly detected



UV image: two spots of corona discharge detected

5.4 Multi-Spectral Inspection Workflow

Effective inspection programs integrate multiple detection domains to capture different aspects of asset condition. Ultraviolet and thermal imaging address electrical behavior, while RGB imaging provides physical context.

5.5 Why RGB Still Matters

RGB visual inspection does not measure electrical stress or heat, but it provides essential structural and environmental context.

RGB imaging can identify:

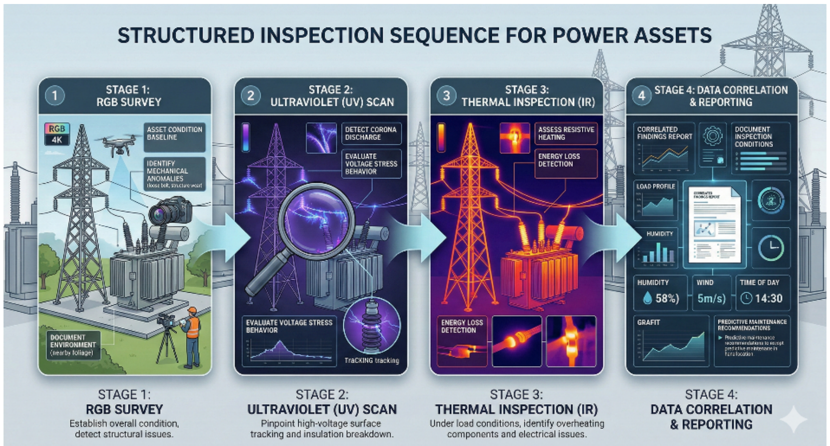
- Cracked or chipped insulators
- Surface contamination
- Missing or damaged hardware
- Corrosion
- Mechanical deformation
- Installation irregularities

Visual documentation supports maintenance crews by linking electrical findings to observable physical conditions.

5.6 Recommended Field Workflow

A structured inspection sequence may include:

1. RGB survey to establish asset condition, identify mechanical anomalies, and document environment.
2. Ultraviolet scan to detect corona discharge and evaluate voltage stress behavior.
3. Thermal inspection under appropriate load conditions to assess resistive heating and energy loss.
4. Correlation of findings and documentation of inspection conditions including load, humidity, wind, and time of day.



Power asset inspection field workflow

5.7 Data Capture Requirements

Reliable interpretation depends on consistent data acquisition practices.

Inspection teams should ensure:

- Consistent distance, focus, zoom, and measurement scale
- Proper temperature range settings for thermal imaging
- Adequate UV sensitivity
- Recording of metadata including load level, humidity, wind conditions, ambient temperature, and time of day

Repeatability is essential for trending. Capturing consistent imagery under comparable conditions enables meaningful comparison over time.

6. Summary: Complementary Technologies Across the Failure Curve

Ultraviolet and thermal imaging detect different physical mechanisms within high-voltage systems.

Ultraviolet imaging reveals voltage-driven electric field stress and corona partial discharge. Thermal imaging reveals current-driven resistive heating and energy loss.

In certain scenarios, corona PD activity may be visible before measurable temperature rise develops. In others, resistive heating may be the first observable indicator.

Neither technology replaces the other. Together, and supported by RGB visual inspection, they provide a comprehensive view of asset condition across the electrical failure progression.

Parameter	**Ultraviolet (UV)**	**Thermal (Infrared)**	**RGB Visual**
Governing Phenomenon	Electric field ionization	Temperature rise	Reflected visible light
Detects	Corona and surface partial discharge	Resistive heating, overload	Physical condition
Primary Driver	Voltage stress	Current flow	Visual observation
Load Requirement	Not load-dependent	Requires sufficient load	Not load-dependent
Typical Detection Stage	Early to mid-stage	Mid to late-stage	Any stage (visual evidence only)
Influenced by Humidity	Yes, can increase visibility	Minor effect	Minimal
Influenced by Wind	Minimal	Yes, can cool components	Minimal
Solar Influence	Not affected by solar radiation	Solar reflections possible	Dependent on lighting
Indicates Energy Loss	Minimal at early stage	Yes	No
Primary Strength	Early detection of voltage stress	Quantifies heating	Context and documentation
Best Used For	Field stress anomalies	Load-related deterioration	Mechanical and surface inspection
Complementary Role	Reveals stress before heating	Confirms resistive damage	Provides physical context

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