Augmented Virtuality and Infrared Radiation Sensing for HVDC Valve Monitoring

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ABSTRACT

High-voltage direct current (HVDC) converter valves are critical assets for transmitting large-scale power from generation hubs such as Itaipu Binational to Brazil's major load centers. However, recent incidents—such as the 2,032-hour outage caused by the 2019 fire in Porto Velho, the 2022 fire at IE Madeira Pole 4, and a capacitor failure at Furnas in 2023—have highlighted the shortcomings of periodic, manual inspections. To overcome these challenges, we propose a cloud-native, TRL 7/8 monitoring system that integrates Augmented Virtuality, parametric Building Information Modeling (BIM), and AI-enhanced infrared thermography to enable continuous, predictive maintenance. A detailed BIM model—including components like thyristors, toroidal inductors, and corona rings—acts as the digital twin's structural backbone. Real-time data from high-resolution thermal cameras (sub-0.05 °C NETD, ≥30 Hz frame rate, compliant with HVDC hall conditions) is spatially aligned with the BIM geometry, enabling per-device thermal tracking and context-aware alerts. Convolutional–transformer neural networks learn the normal spatiotemporal heat patterns of each device and detect anomalies before SCADA limits are breached. A state-machine layer correlates thermal anomalies with electrical events captured via SAP/SAGE systems. All telemetry is securely stored in a Google Cloud-based data lake for long-term archiving and AI model retraining. Diagnostics are visualized using Autodesk Platform Services and ArcGIS dashboards, providing 3D overlays accessible through tablets or head-mounted displays directly inside converter halls. Initial validation was conducted with fixed thermal cameras at Araraquara's converter station, demonstrating high-quality imaging under energized conditions and seamless control-room integration. Full-scale implementation at Eletronorte's Porto Velho and Araraquara terminals is planned over a 24-month roadmap. The system is expected to reduce unplanned outages, extend equipment lifespan through condition-based maintenance, and reduce on-site exposure for maintenance teams. Built on ISO 19650-compliant BIM and commercial edge hardware, it offers a scalable digital twin solution for HVDC infrastructure monitoring.

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INTRODUCTION

High-voltage direct-current (HVDC) interconnectors are the backbone of Brazil's long-distance power-transfer system (NS Energy Business, 2025), funneling up to 7.1 GW over the 2 375 km Porto Velho–Araraquara link and 6 GW along the twin 600 kV Itaipu bipoles, while incurring far lower transmission losses than the parallel AC grid (Furnas,2011). Although these schemes were once heralded for exemplary reliability, three major incidents in the past decade have exposed the vulnerability of valve halls to silent thermal degradation and insulation breakdowns: a saturable-reactor fire in Porto Velho in 2019 that kept Bipole 1 out of service for 2032 h; an internal component failure that ignited Pole 4 of IE Madeira in June 2022; and the 2023 blaze that derated Foz do Iguaçu Converter 4 by 800 MW and triggered a R$ 2 billion fleet-modernization program at Eletrobras (ADVFN Brasil, 2025). Post-event forensics showed that no SCADA or vendor "InTouch" console raised pre-alarm flags, revealing how periodic walk-throughs and threshold-based alerts fail to detect the subtle thermal drifts that precede silicon breakdown and cooling-system blockage (Itaipu Binacional,2025).

Concurrently, four technological strands have matured to the point where they can be woven into a continuous-monitoring paradigm: (i) semantically rich Building Information Modeling (BIM) (Cardoso,2017); (ii) cloud-hosted digital twins capable of ingesting live telemetry; (iii) rugged, high-resolution infrared (IR) imagers with < 0.05 °C NETD; and (iv) deep-learning architectures that learn spatio-temporal heat signatures at device level. Recent R\&D conducted by CGWorks, the Federal University of Uberlândia and Eletronorte has already produced granular 3-D BIM replicas of the Porto Velho and Araraquara valve halls and demonstrated Augmented- and Virtual-Reality (AR/VR) procedures for guided maintenance and operator training (Dalle,2015). Building on that foundation, this paper proposes a cloud-native architecture in which real-time IR thermograms and electrical measurements from every thyristor tray are spatially registered to the BIM model, elevating it to a living digital twin (Masood,2020). Transformer-based deep-learning models continuously learn each valve's normal thermal fingerprint, flagging incipient hotspots long before conventional limits are breached, while AR overlays projected on tablets or head-mounted displays let field crews visualize anomalies directly on the 3-D geometry (Gerson Lima,2023). Bidirectional links with SAP/SAGE SCADA systems feed actionable diagnostics back to the control room, and a secure Google-Cloud data lake preserves the full telemetry record for trend mining, model retraining and enterprise knowledge-sharing (INESC,2022).

A pilot deployment across Eletronorte's Porto Velho and Araraquara terminals will evaluate the platform against three metrics—reduction of unplanned outages, extension of valve-stack lifetime through condition-based scheduling, and improved occupational safety by reducing human exposure inside the valve halls. Because the workflow adheres to ISO 19650 information-management principles and relies on commercial off-the-shelf edge hardware, it is readily transferable to other HVDC links and large-scale power-electronics installations, offering a replicable blueprint for a digitally resilient, data-driven transmission grid.

OBJECTIVES

To enhance the operation and maintenance of HVDC substations, the Virtual and Augmented Reality system previously developed for Eletrobras Eletronorte (R&D Project) is being adapted to meet the specific demands of high-voltage converter environments. This evolution incorporates parametric BIM modeling and semantic integration of infrared sensing data, enabling the system to establish direct associations between thermal behavior and physical components such as thyristors, toroidal inductors, capacitors, cooling units, pump houses, optical fibers, and Optical Distribution Frames (ODFs). The implementation is tailored to reflect the actual physical configurations of the Porto Velho (RO) and Araraquara (SP) terminals.

At the core of the system is a suite of advanced functionalities designed to deliver continuous, intelligent, and context-aware monitoring. Strategically placed high-resolution thermal-infrared cameras ensure complete coverage of the converter valve assemblies, capturing the thermal signatures of all critical components. This thermal imaging is tightly coupled with the BIM environment, forming the basis for a dynamic 3D model that evolves with real-time sensor input.

The monitoring architecture is fully integrated with Eletronorte's SAP and SAGE (SCADA) platforms, creating an autonomous supervisory framework. By leveraging non-conventional sensing methods, AI-driven analytics, and state-machine logic, the system supports an Augmented Virtuality layer for predictive asset management. AI algorithms interpret spatiotemporal patterns to detect early signs of degradation, enabling proactive interventions.

To support ongoing analysis and model refinement, a centralized data infrastructure consolidates historical and real-time thermographic data along with oscillographic signals from electrical systems. The system is designed for uninterrupted 24/7/365 operation—crucial given the harsh conditions inside valve halls and the limited access windows available for manual inspection.

Thermal cameras are specified to meet rigorous operational demands, and computer vision tools continuously analyze data to generate early warnings and actionable insights. Thermal imagery is mathematically registered into the parametric 3D model, enabling spatially accurate visualization and automated inspections. A State Inference Engine links each component to its digital counterpart within the twin, ensuring precise traceability.

This integrated approach, currently under implementation at the Porto Velho and Araraquara terminals, enhances operational resilience by reducing unplanned outages, extending equipment lifespan through condition-based maintenance, and improving safety for maintenance teams.

METHODS

The proposed approach implements a continuous asset-monitoring system that fuses infrared sensing with parametric 3-D BIM models built on the previously developed virtual platform. The workflow starts with real-time thermogram acquisition inside the HVDC valve halls; each image is automatically registered to the granular elements of the 3-D model—thyristors, inductors, cooling channels, and other components. These thermal data streams drive anomaly-detection algorithms that forecast critical failures before conventional operational limits are exceeded. By linking every temperature reading to its corresponding BIM object, the method applies the principle of augmented virtuality, enabling contextual analysis of thermal behavior within a navigable digital environment, as illustrated in Figure 1 and Figure 2.

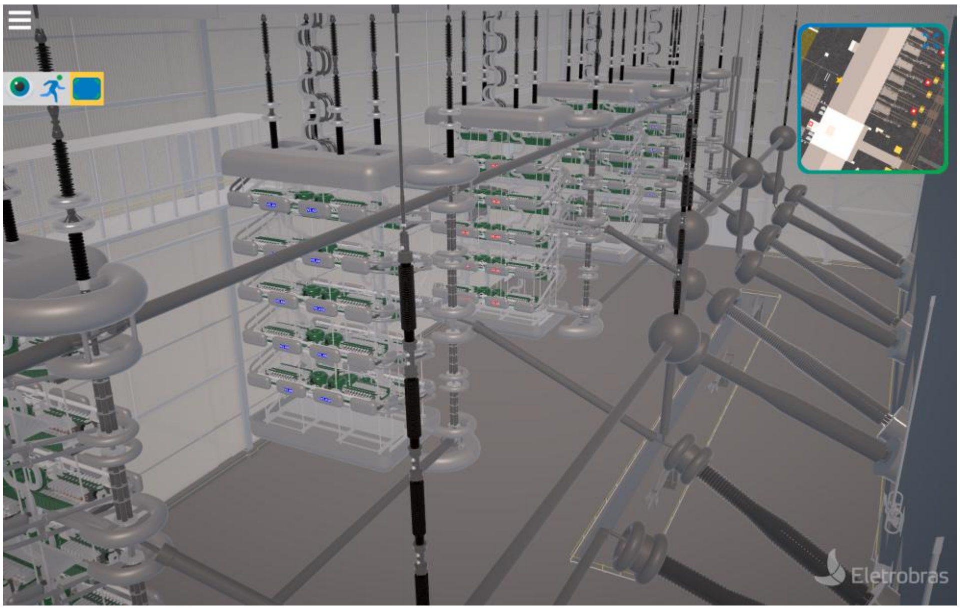

Figure 1 — Perspective view of the 3-D virtual model of the Araraquara HVDC valve hall, Eletrobras Eletronorte (P&D Aneel,2023).

Figure 2 — HVDC converter substation: 500 kV AC yard view, Eletrobras Eletronorte, Araraquara-SP (P&D Aneel,2023).

In Figure 3, a field test of infrared thermal sensing on an offline valve hall is shown alongside a detailed 3-D model of the same valve, depicting its constituent devices—thyristors, corona-equalizing rings, toroidal inductors, cooling circuits, and so forth. Within the scope of this project, these 3-D models must be enriched with BIM parameters so that each component can be linked to its corresponding thermal (infrared) data.

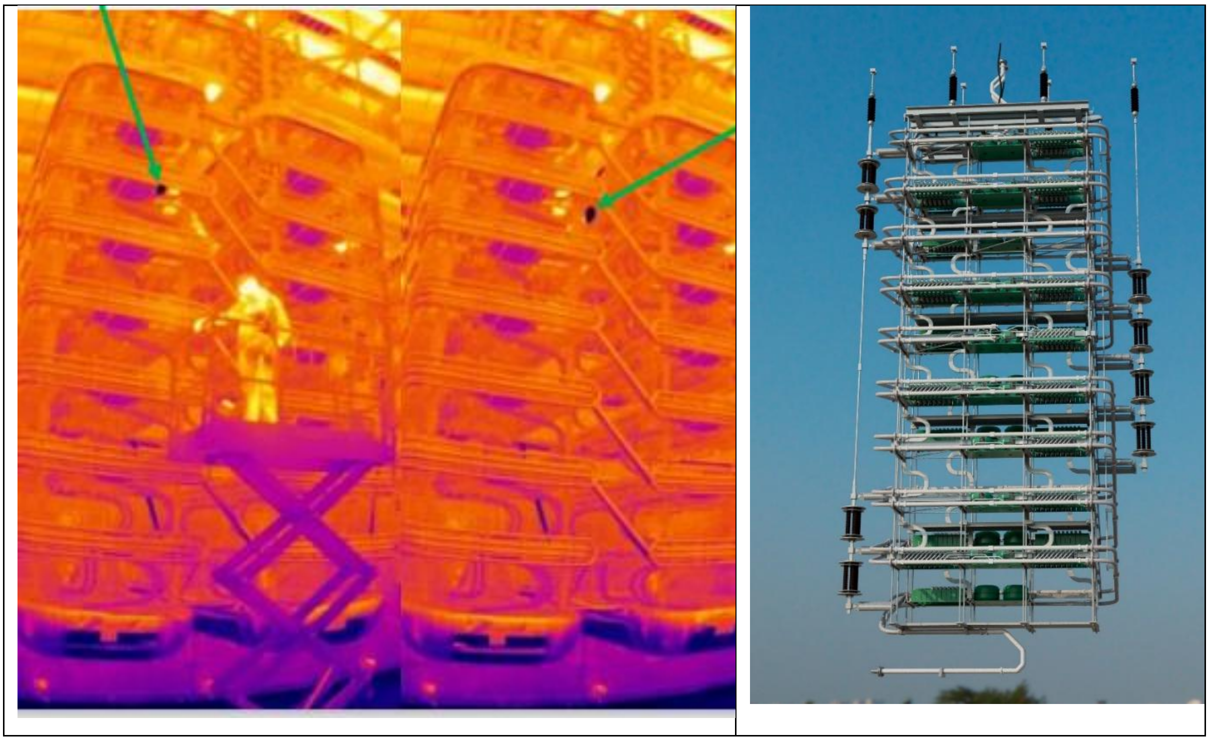

Figure 3 — Infrared thermography of the Araraquara HVDC valve and the corresponding parametric 3-D BIM valve model (Source: Author's 2025).

In this project, the 3-D model is redefined according to the principle of granularity: BIM (Building Information Modeling) objects will be developed parametrically and enriched with explicit attributes—dimensions, materials, thermal properties, and connectivity with neighboring elements. This "compartmentalized" and information-rich structure allows every component to be represented as a node (or group of nodes) in a graph, while positional, functional, and logical relationships are mapped as edges.

Consequently, the BIM models deliver the level of granularity required for graph-based studies, because each construction or infrastructure unit carries metadata that can be explored through network analysis. For example:

1. Nodes (BIM elements) – thyristors, capacitors, inductors, connectors, electronic links, items of equipment, and so forth.
2. Edges (relationships)– physical, spatial, or functional connections between elements, as well as construction-sequence or maintenance dependencies.
3. Attributes – design data (size, material), operational data (temperature, utilization), cost, schedule, and other variables that enrich graph analytics.

In this way, the granular 3-D BIM representation can be translated into graph data, enabling advanced network analyses, failure-impact assessments, and simulations that depend on complex interrelationships among system components. Figure 4 illustrates the concept of Augmented Virtuality integrated with the granular 3-D valve model for the HVDC installation.

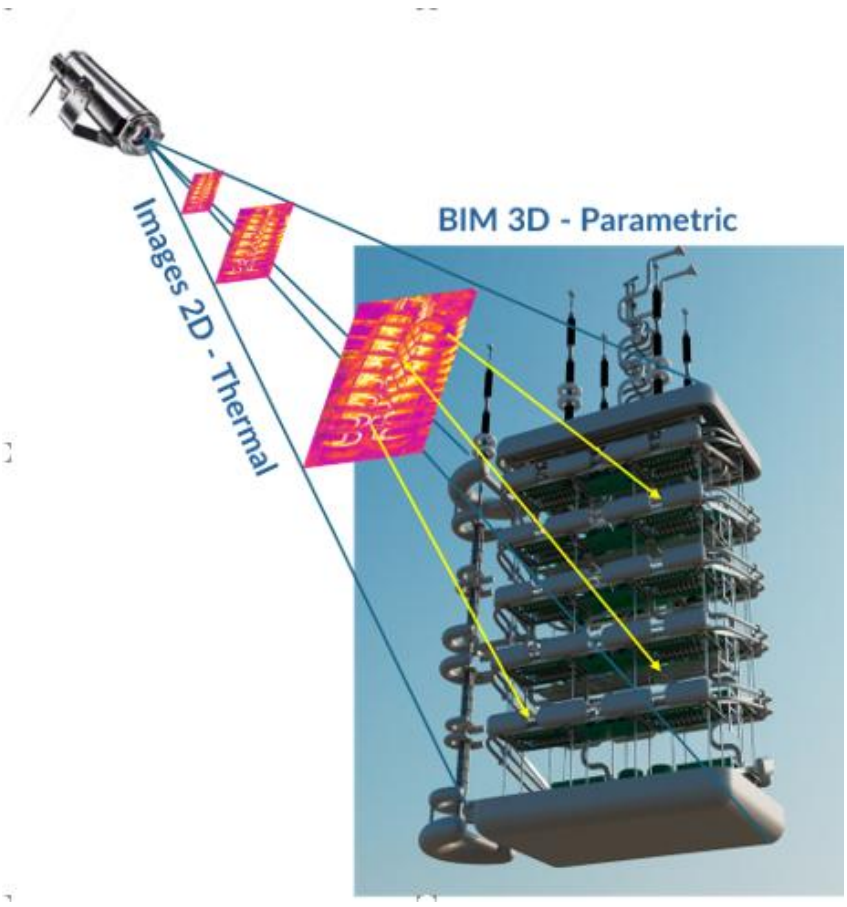

Figure 4 — Augmented Virtuality: Infrared Images vs. 3-D BIM Valve Model, HVDC (P&D Aneel,2023).

SYSTEM ARCHITECTURE

Thermal cameras mounted inside the valve hall continuously capture IR frames for every critical thyristor module, toroidal inductors, cooling channels, and so on. Each frame is streamed across the plant network to **Google Cloud**

Storage, where it is versioned and catalogued. At the same moment, component metadata from the granular 3-D BIM model (element ID, position, class) are written to a companion table in **Big Query**, creating a one-to-one "pixel-to-part" link.

A **Cloud Function** is triggered whenever new imagery lands in the bucket. It registers the thermogram to the matching BIM element and pushes a message to a containerized inference pipeline running on **Google Cloud Run**. The pipeline performs three stages:

1. **Data preparation** – normalizes temperature values, merges SCADA electrical readings, and fetches the component's geometry from the BIM graph.
2. **Model inference / training** – deep-learning models compare the incoming thermal profile with the learned baseline for that specific node, quantifying deviations in real time.
3. **Output generation** – produces hotspot alerts, asset-health indices, and georeferenced heat maps anchored to the 3-D mesh.

Outputs and accuracy metrics are written back to Storage/BigQuery for audit and retraining. Dashboards in **Power BI** and interactive plots in **Plotly** render the anomaly within seconds, overlaying it on the navigable BIM model. Field and control-room staff can therefore pinpoint the affected component, plan interventions, and maintain a continuous 24 × 7 predictive-maintenance loops fully integrated with the HVDC valve-hall digital twin, Figure 5.

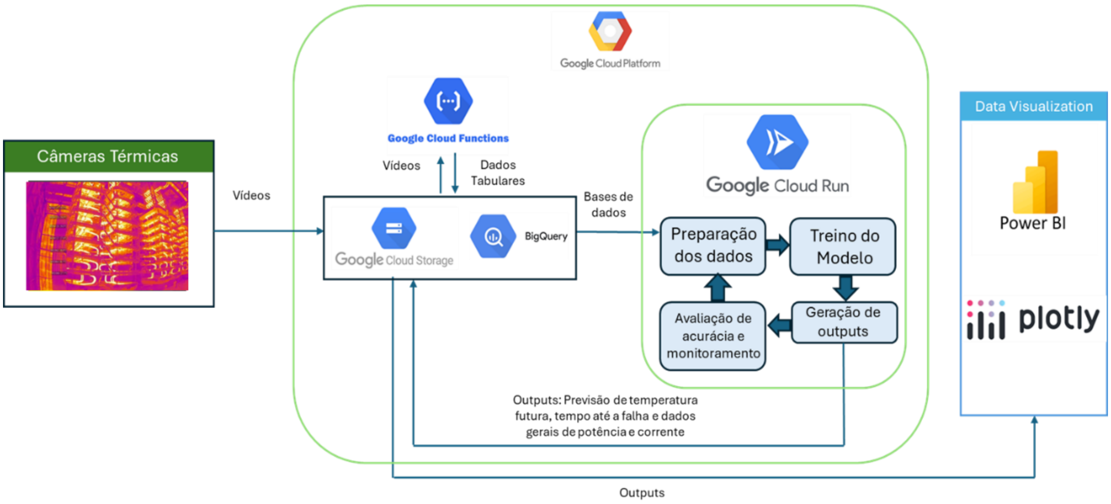

Figure 5 — Cloud-based system for storing thermal-vision images and data – HVDC (Source: Author's 2025).

In parallel with the image-processing and anomaly-detection pipeline, the system establishes a robust integration between the granular BIM model and supervisory control databases specifically SAP (asset and maintenance management) and SAGE (real-time SCADA). Each BIM object representing a physical device such as a thyristor or cooling module is assigned a persistent identifier that matches the tag structure used in SCADA and SAP records. This enables bidirectional linking of geometry, metadata, and telemetry. For example, when an anomaly is detected on a BIM-linked component, the system can immediately query the SCADA history to retrieve voltage, current, or triggering event logs, and consult SAP for recent maintenance records or failure reports related to that device. Conversely, events registered in SCADA such as voltage sags or temperature spikes can trigger spatial localization and visualization within the BIM interface, allowing operators to isolate the affected device in 3D and assess its context. This deep coupling between the parametric model and real-time telemetry transforms the BIM environment into an intelligent diagnostic interface capable of supporting precise, context-aware maintenance decisions. As a result, predictive maintenance is no longer based solely on static thresholds or isolated signals but emerges from the cross-analysis of operational history, spatial configuration, and real-time sensing.

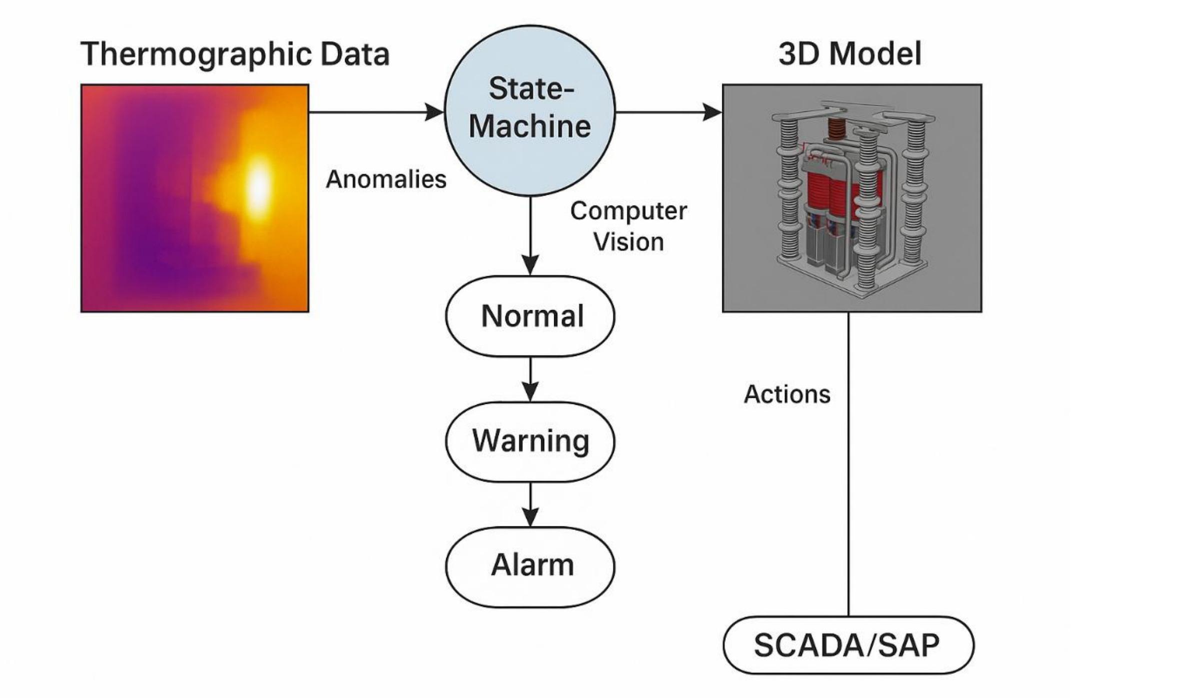

Figure 6- State-Machine Diagram Integrating Thermographic Data with 3D Parametric Models via Computer Vision. (Source: Author's 2025)

The proposed architecture (Figure 6) links thermographic data to granular BIM models through a state-machine engine powered by computer vision algorithms.

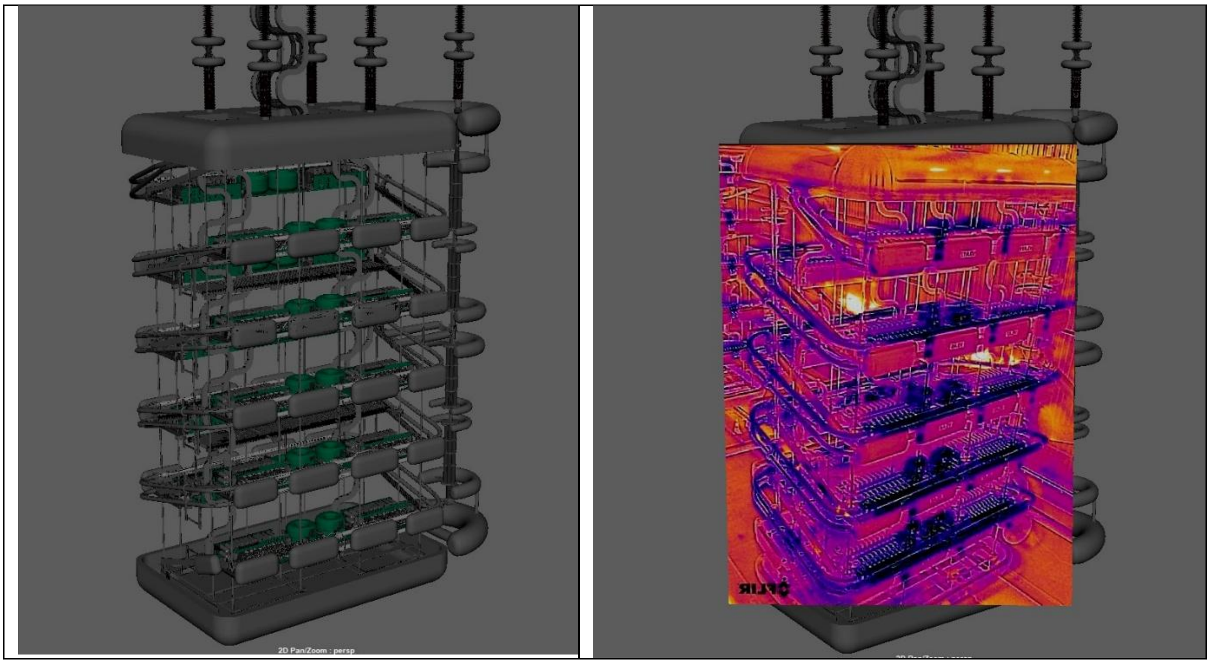

Figure 7- Infrared and 3D Model coupled into the monitoring system (Source: Author's 2025)

Anomalies detected by infrared cameras are spatially registered to specific HVDC valve components within the 3D model. Transitions between operational states (Normal, Warning, Alarm) are triggered based on learned thermal patterns (Figure 7). Resulting actions are integrated into SCADA/SAP systems, enabling automated decision-making, predictive maintenance, and real-time supervision of physical assets

EXPECTED OUTCOMES AND EARLY VALIDATION

As the project is still in its early implementation phase, the benefits outlined below represent expected outcomes that will serve as key metrics for evaluating the solution's effectiveness during the forthcoming development and deployment stages.

The system is designed to run continuously (24 × 7 × 365) in the harsh electromagnetic and thermal environment of HVDC valve halls, predicting critical failures far enough in advance to allow planned interventions. This capability will stem from the fusion of high-resolution thermal cameras with edge-based computer-vision algorithms that analyses thermograms in real time and generate predictive alerts for operators.

By applying augmented virtuality*, infrared imagery will be overlaid onto parametric 3-D BIM models, enabling automated, context-rich inspections of each component thyristors, inductors, cooling channels, and more while feeding a relationship graph that underpins advanced diagnostics. Detected events will be routed to the SCADA/SAGE system via bidirectional links, enabling rapid, data-driven responses, while state-machine agents will automate strategic decisions and fine-tune maintenance routines.

Expected results:

-Prevention of major incidents early detection of overloads, hotspots, and thermal failures, averting fires and irreversible asset damage.
-Lower operational costs predictive maintenance and failure prevention eliminate emergency repairs and losses due to downtime.
-Extended asset life continuous monitoring minimizes component wear and maximizes durability.
-Enhanced operational efficiency integrated information improves management capacity and the prioritization of interventions.
-Real-time diagnostics continuous analysis identifies thermal and visual anomalies remotely and non-intrusively.
-Parametric, strategic decision-making cross-referencing thermal, visual, and electrical data enables advanced diagnostics and automated decisions.
-Process automation augmented-virtuality agents support strategic decision-making, preventing critical failures and optimizing operations.

SCIENTIFIC AND TECHNOLOGICAL CONSTRIBUTIONS

This research introduces a set of technological innovations that significantly advance the current state of the art in monitoring and predictive maintenance of high-voltage direct current (HVDC) substations. At its core, the project delivers one of the first real-world applications of an Augmented Virtuality framework within live HVDC converter halls. By integrating infrared thermography with parametric Building Information Modeling (BIM) and real-time data streams, the system forms a dynamic digital twin environment that enhances visibility, control, and decision-making across critical components of the converter infrastructure.

A central contribution of the work is the development of a "pixel-to-part" mapping methodology, which enables spatial registration of 2D thermal imagery to 3D BIM elements with high precision. This alignment supports fine-grained diagnostics at the component level—such as thyristors, toroidal inductors, capacitors, and cooling systems—allowing the maintenance team to identify and act upon early signs of thermal anomalies with greater confidence and contextual awareness. Complementing the spatial intelligence of the system, edge-deployed deep learning models are used to perform continuous monitoring of thermal patterns.

These transformer-based networks are capable of learning the normal operating behavior of each component and issuing early alerts when deviations occur, often well before conventional SCADA systems would trigger alarms. This proactive approach enables predictive diagnostics that reduce unplanned downtime and extend asset life. The system also incorporates a graph-based asset health model, where each physical component is represented as a node within a network enriched with real-time operational metadata.

This graph architecture enables advanced analyses, including fault propagation modeling and impact assessment, facilitating informed and timely maintenance strategies. Importantly, all developments are validated under real operational conditions, specifically within the energized environment of Eletronorte's Araraquara converter terminal. This field deployment confirms the Technology Readiness Level (TRL) of 7/8, demonstrating the robustness of the system's hardware, algorithms, and data integration workflows. Built on an ISO 19650-compliant architecture and utilizing commercially available edge hardware, the system is scalable and transferable across different HVDC contexts. Its design aligns with broader digital transformation goals in the energy sector, ensuring interoperability, maintainability, and long-term sustainability.

Finally, the modular nature of the platform and the documented implementation methodology establish a reproducible blueprint for AI-enhanced maintenance in power electronics. The approach sets a foundation not only for future deployments in other HVDC schemes but also for ongoing research in digital twins, computer vision, and intelligent asset management within high-voltage, mission-critical environments.

CONCLUSION

The monitoring architecture described here marks a decisive leap forward in the supervision and upkeep of high-voltage direct-current (HVDC) valve halls. It unites high-resolution infrared sensing, advanced thermographic analytics, and augmented-virtuality visualization within a granular, parametric BIM digital twin yielding a live, data-rich model that traces the thermal fingerprint of every thyristor, inductor, and cooling channel in real time.

The thermograms are automatically registered to their corresponding BIM elements, scrutinized at the edge by computer-vision routines, and forwarded to a cloud data lake where predictive algorithms flag nascent hotspots days or even weeks before traditional alarms would react.

This end-to-end workflow will be piloted at the Porto Velho and Araraquara converter stations. Full integration with the existing SCADA/SAGE layer and alignment with Eletronorte’s refurbishment and R&D programs ensure smooth adoption and immediate operational value.

Crucially, the solution provides a scalable template for digital-twin monitoring across Brazil’s entire HVDC fleet and other power-electronics assets. By pairing edge analytics with cloud-level elasticity and rich BIM semantics, it bolsters the reliability, efficiency, and resilience of the national transmission grid while delivering tangible economic savings and enhanced energy security.

ACKNOWLEDGEMENTS

The authors would like to thank *Eletrobras Eletronorte* and *National Electric Energy Agency* ANEEL for all the support provided in the R&D (Research and Development) project, contract 4500062446.Additionally, the authors thank the technological and structural support from the *Virtual and Augmented Reality Group* (GRVA) and the *Computer Graphics Works llc* (CGW).

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