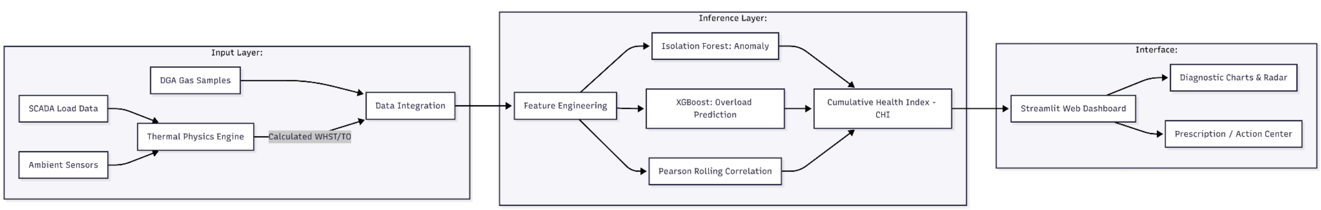
Transformer Thermal Monitor (TTM) Foundation Model

1. Executive Summary

The **Transformer Thermal Monitor (TTM)** is a high-fidelity "Digital Twin" and diagnostic engine engineered for the predictive maintenance of critical high-voltage assets. Specifically calibrated for a **70 MVA ONAN Transformer**, the system architecturally blends rigorous industrial physics based on the **IEC 60076-7** standard with modern, high-performance Machine Learning frameworks like **XGBoost** and **Isolation Forest**. This manual provides a deep-dive into the underlying mathematical logic, the feature engineering pipeline, and the software deployment strategies used to encapsulate a complex Python ecosystem into a portable, error-free Windows application.

2. System Architecture & Information Flow

The system operates as a modular pipeline where raw physical data is enriched by a thermal engine before being analyzed by the AI layer for real-time decision support. This architecture ensures that the machine learning models are "physics-aware," meaning they understand the thermodynamic limits of the hardware they are monitoring.



3. Library Ecosystem & Usage Reference

The following libraries form the "Cellular Structure" of the TTM application, each serving a specific role in maintaining the integrity of the diagnostic pipeline:

- **pandas (Data Management):** Handles high-resolution time-series alignment. It ensures sensors for electrical load, chemical DGA samples, and ambient readings—which often report at different frequencies—are synchronized into a unified feature vector for the AI.
- **numpy (Physics Solver):** Used for the Euler integration of thermal differential equations, modeling the physical reality that temperatures follow a lagged, exponential response rather than instantaneous changes.
- **scikit-learn (Anomaly Detection):**
  - Isolation Forest: Identifies outliers spatially distant from the "normal" cluster. This is

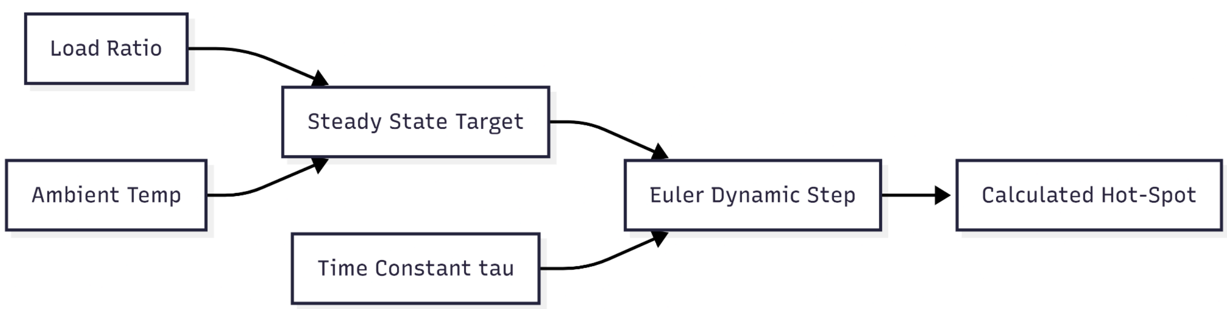
particularly effective for detecting "silent" failures like gradual radiator clogging or minor partial discharges.
    - StandardScaler: Rescales diverse data types (e.g., 150kV vs 0.05ppm) onto a shared mathematical scale, preventing large magnitude variables from biasing the models.
- **xgboost (Predictive Intelligence):** Predicts the "Max Safe Overload" limit by learning non-linear relationships between ambient heat, cooling status, and internal thermal constraints. It provides the "forecasting" capability that allows operators to plan load shedding.
- **psutil (Process Control):** Monitors active sessions and acts as the "Executioner" to clean up background tasks once the user hits "Shut Down," ensuring no memory leaks occur on the host machine.

4. The Thermal Foundation (Physics Layer)

The generation engine in synthetic_data.py is strictly rooted in the **IEC 60076-7:2018** international standard, which provides the mathematical framework for loading power transformers.

4.1 Top-Oil & Hot-Spot Dynamics

The model calculates the **Winding Hot-Spot Temperature (θ_{hs})**, which is the absolute highest temperature any part of the winding insulation reaches, in two distinct stages:



1. **Steady State Target:** The "ultimate" temperature reached if load and ambient stayed constant forever. This is governed by the load ratio (K) and the loss ratio (R), which defines the relationship between copper losses and iron losses.
2. **Dynamic Euler Step:** Uses a **Thermal Time Constant (τ)** (210 minutes for oil) to ensure temperatures "glide" realistically. This accounts for the significant thermal inertia of 32,000kg of oil, preventing the AI from flagging normal thermal lags as faults.

4.2 Insulation Aging (NEI)

The "Normal Expected Insulation" life of a transformer is defined by the mechanical strength of its paper insulation, measured by the **Degree of Polymerization (DP)**.

- **Aging Rate (V):** Uses the Arrhenius equation. At 110°C, $V = 1$. At 116°C, the speed doubles ($V = 2$), meaning the transformer consumes 48 hours of design life for every 24 hours of operation.
- **DP Degradation:** The model starts at a "New" value of 1100. When it drops to 200, the paper becomes brittle and loses its tensile strength, marking the technical "End of Life."

5. Machine Learning Engine (AI Layer)

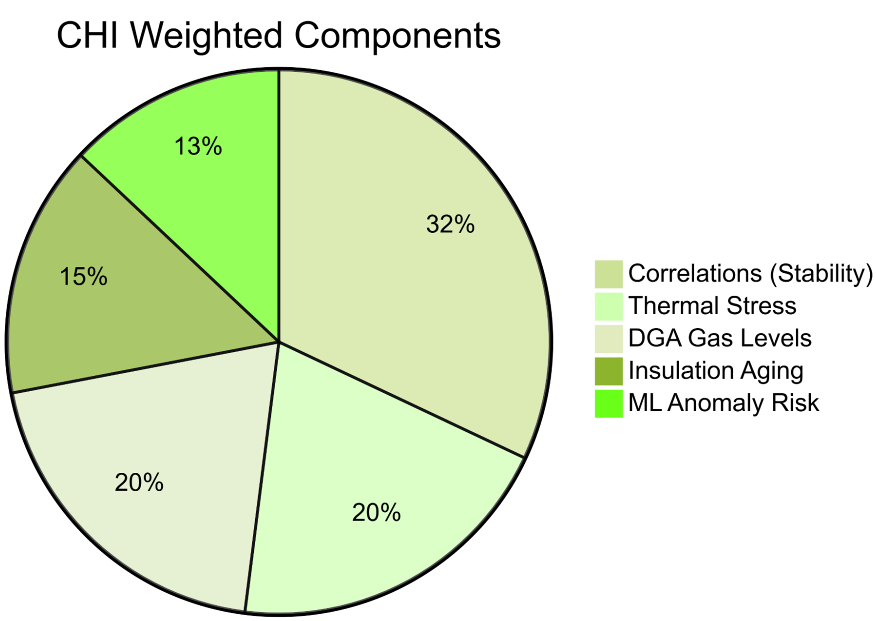
5.1 3-Way Correlation Analysis

The system performs a continuous "Sanity Check" on the physical bonds between **Load**, **Temperature**, and **Gas**. This is the core of diagnostic intelligence.

- **The Physics Bond:** Normally, $Load \uparrow \implies Temp \uparrow \implies Gas \uparrow$.
- **The Fault Logic:** If the electrical load is decreasing but the oil temperature continues to rise or stay high, the **Pearson Correlation (ρ)** will drop toward zero. This mathematical decoupling immediately flags a "COOLING_ISSUE," alerting the operator to check the radiators.

5.2 Cumulative Health Index (CHI)

The CHI is a unified score (0-100) that provides an executive-level summary of asset health by weighting five sub-indices:



6. Dashboard Functionalities & Visualization

The dashboard provides a multi-perspective view of transformer health through interactive charts:

- **Overview Tab:** A dual-axis chart showing **Load %** vs. **WHST**. It allows operators to visually confirm if the cooling system is responding to load changes. It also includes the **CHI Trend**, which plots the health score over time to identify slow degradation vs. sudden failures.
- **Health Index Tab:** Features a **Radar Chart (Spider Chart)**. This is designed for instant pattern recognition. A healthy transformer is a tiny dot at the center. As stress grows (DGA, Aging, or Anomalies), the radar "stretches" toward specific axes, showing an engineer exactly where the trouble lies.
- **Overload Tab:** A **Predictive Bar Chart** showing the "Safe Window" in hours for various overload levels. For example, it might show that a 120% load is safe for 3.5 hours, but a 140% load is safe for only 20 minutes before insulation damage occurs.
- **Prescription Tab:** The "Action Center." It converts complex AI math into plain-English instructions (e.g., "Activate Stage 2 Cooling Fans" or "Reroute 5MW via tie-breaker") based on which quadrant the fault lies in.

7. Glossary for Non-Domain Experts

- **MVA (Mega-Volt Ampere):** The power capacity (size) of the transformer. Larger transformers have more MVA.
- **ONAN:** Oil Natural Air Natural. A transformer cooled by natural oil circulation and air flow, without pumps or fans.
- **DGA (Dissolved Gas Analysis):** A chemical "blood test" for oil. Different gases indicate different faults (e.g., Acetylene indicates arcing).
- **WHST (Winding Hot-Spot Temp):** The absolute hottest point inside the transformer windings. This is the temperature that directly causes failure.
- **Pearson ρ (Correlation):** A value between -1.0 and 1.0; 1.0 means two things are moving perfectly together, while 0 means they have no relationship.
- **p.u. (Per Unit):** A normalized way of comparing values (1.10 p.u. load = 110% load). It allows engineers to compare different sized transformers easily.