# Verify & Validate + Calibrate Tool (V²Cal) for Automated Model Parameters Tuning

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# MOD-026-2 (new approved NERC standard)

- **MOD-026-2 replaces MOD-026-1 and MOD-027-1**
  - **MOD-026-1:** validation of excitation / Volt-Var control models
  - **MOD-027-1:** validation of turbine-governor / frequency-power control models
- MOD-026-2 expands validation to **modern BPS resources**, including **IBRs, FACTS, HVDC, and synchronous condensers**
- **EMT simulation is important** for large disturbances because it captures fast controls, nonlinear behavior, and protection actions that **positive-sequence models may miss**
- **Positive-sequence models** are still used for bulk planning studies, but they should be checked against **EMT model response** for severe events
- **Model validation is essential** to ensure study models match actual field behavior and produce credible planning results

https://www.nerc.com/standards/reliability-standards/mod/mod-026-2

# $V^2$Cal: Verify & Validate + Calibrate Tool

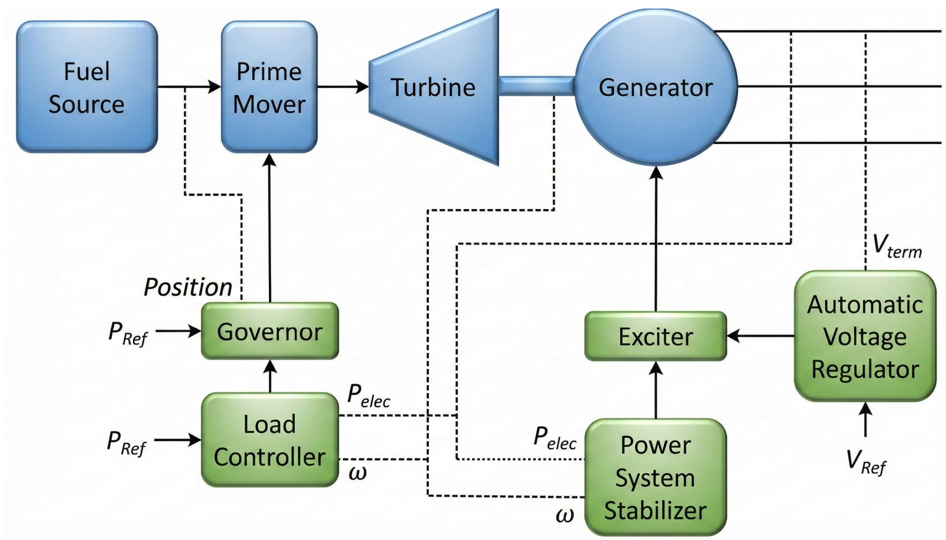
- $V^2$Cal is a Python-orchestrated workflow that automates end-to-end play-in studies.
  - Supports PSS®E with extensibility to PSLF/PowerWorld and EMT solvers
  - Ingests PMU/DFR (SCADA optional), prepares channels, builds cases
  - Runs simulations, sensitivity analysis, and Bayesian calibration
  - Produces interactive, shareable HTML reports
  - Replaces manual data prep and tuning, reducing analyst burden and streamlining measurement-based verification
  - Supports NERC MOD studies by streamlining measurement-based model verification and validation workflows

- Will be released on GitHub (pending DOE approval): https://github.com/pnnl/v2cal

# Power Plant Model Verification

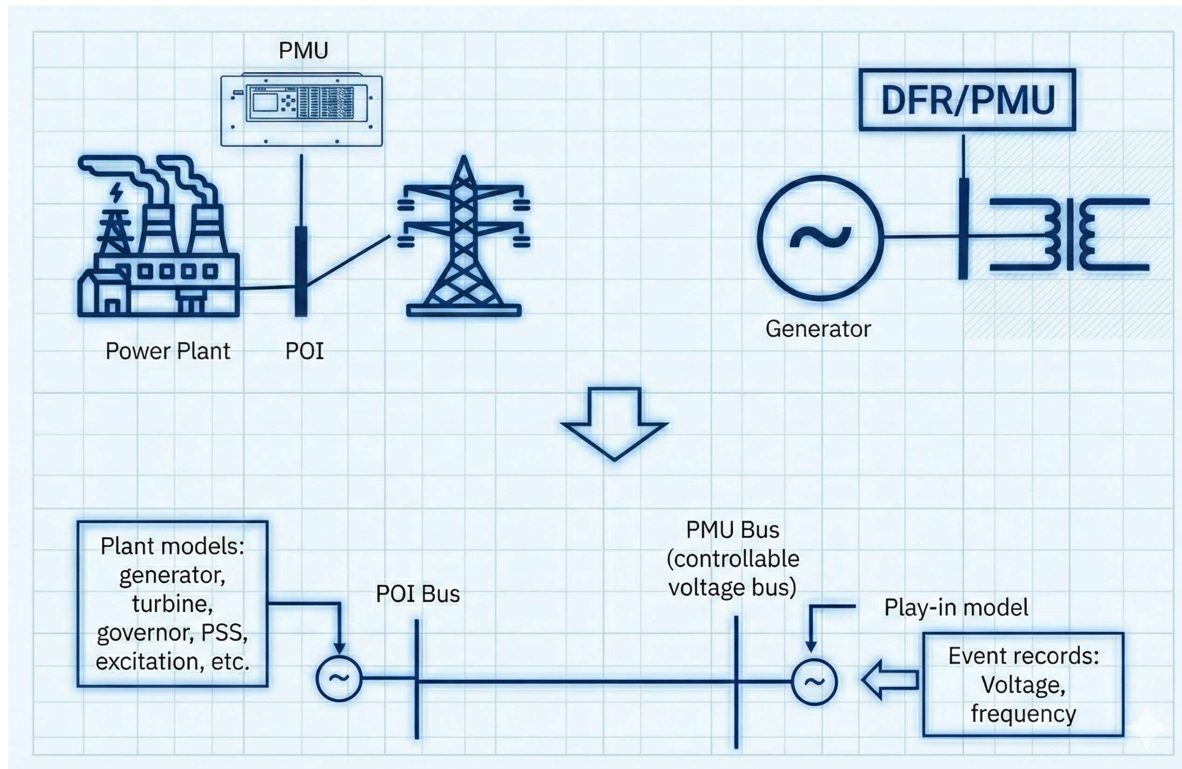
- Verify model structure
- Verify model parameters
- Scope typically includes:
  - Generator (synchronous machine)
  - Turbine – Governor
  - Excitation system/AVR
  - Power system stabilizer (PSS)
  - If applicable: limiters, turbine load controller, protection

Conventional Power Plant Structure



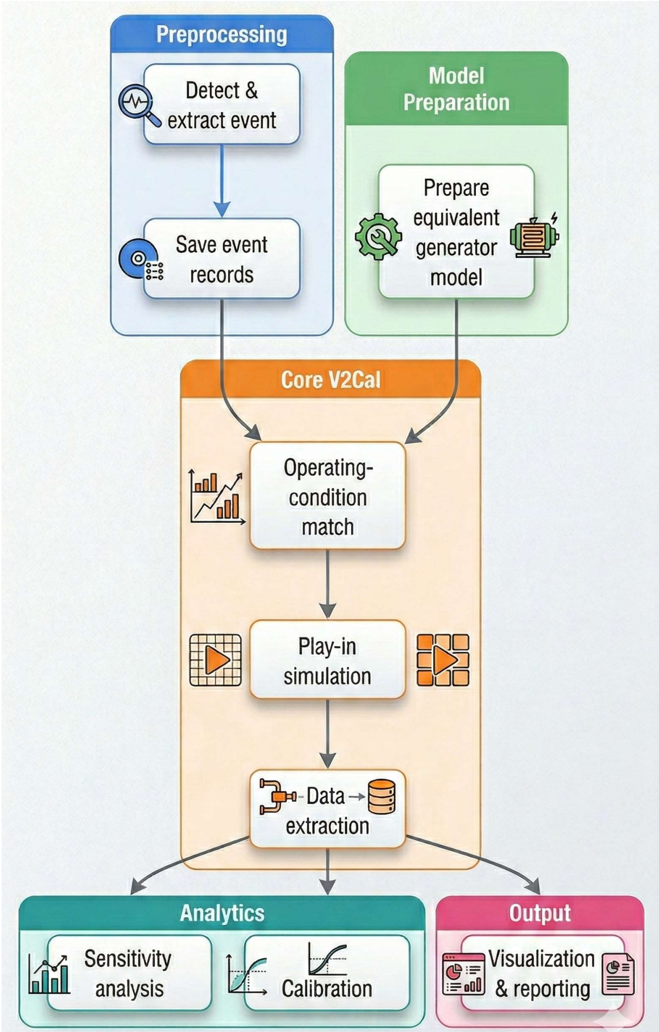
# Play-in Model Validation

- **Data Requirement:** High-fidelity PMU/DFR data at the POI or Generator.
- **Method:** "Play-in" recorded Voltage/Frequency as a controllable source during simulation.
- **Benefit:** Enables validation of specific plant components (e.g., Governor, Exciter) without simulating the full network.



# V²Cal Workflow Overview

- Initial data preprocessing
  - Detect and extract disturbance event
  - Save event records in PSS®E-compatible CSV format
- Model preparation - Build/prepare the equivalent generator model for play-in studies
- Core V²Cal modules
  - Operating-condition matching between power-flow case and measurements
  - Play-in simulation (main validation step) using measured V/F as inputs
  - Data extraction from binary channel files
- Visualization & reporting - Generate interactive, shareable HTML reports
- Additional analytics
  - Sensitivity analysis to identify impactful parameters
  - Calibration of model parameters using Bayesian optimization



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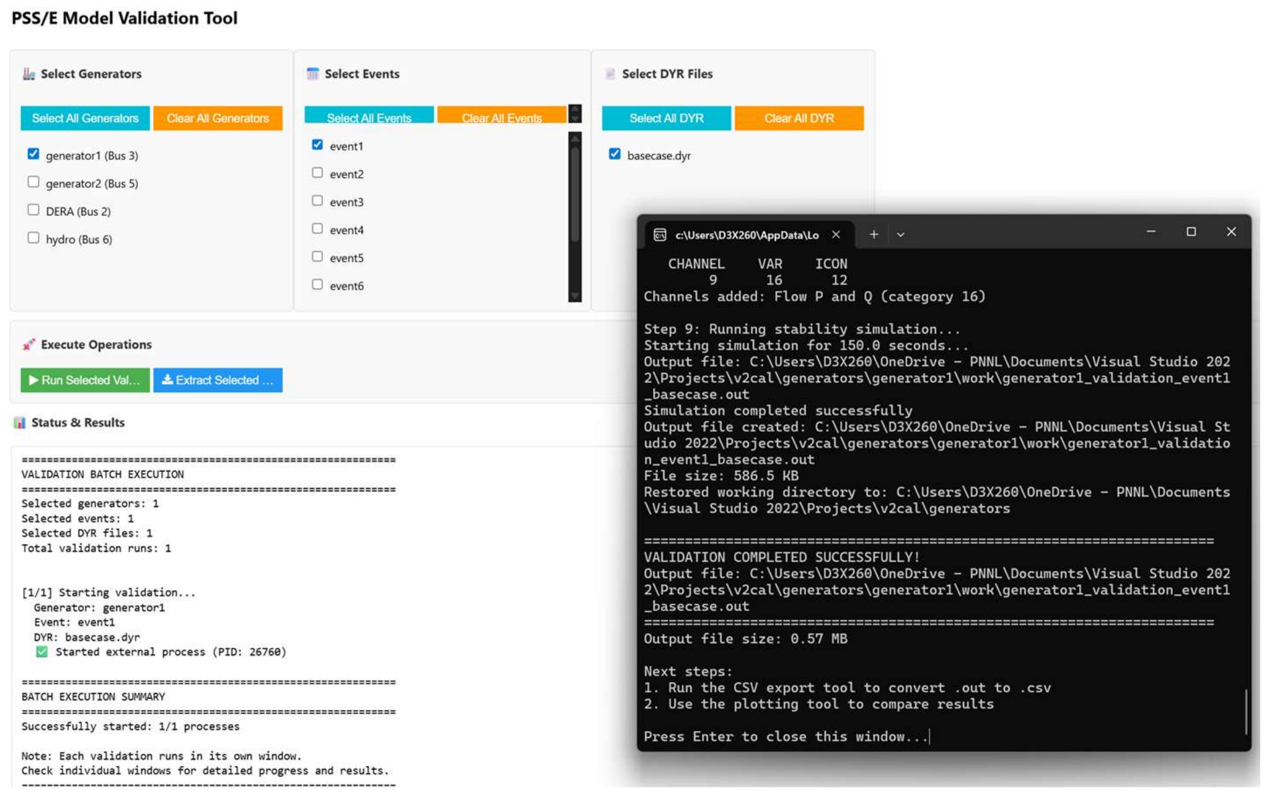
# V²Cal Architecture

- Pure Python application
- GUI implemented in Jupyter Notebook
- Easy to install, setup and run
- Communicates with PSS®E through native Python API
- Transparent, easy-to-modify codebase compared to previously developed PPMV tool



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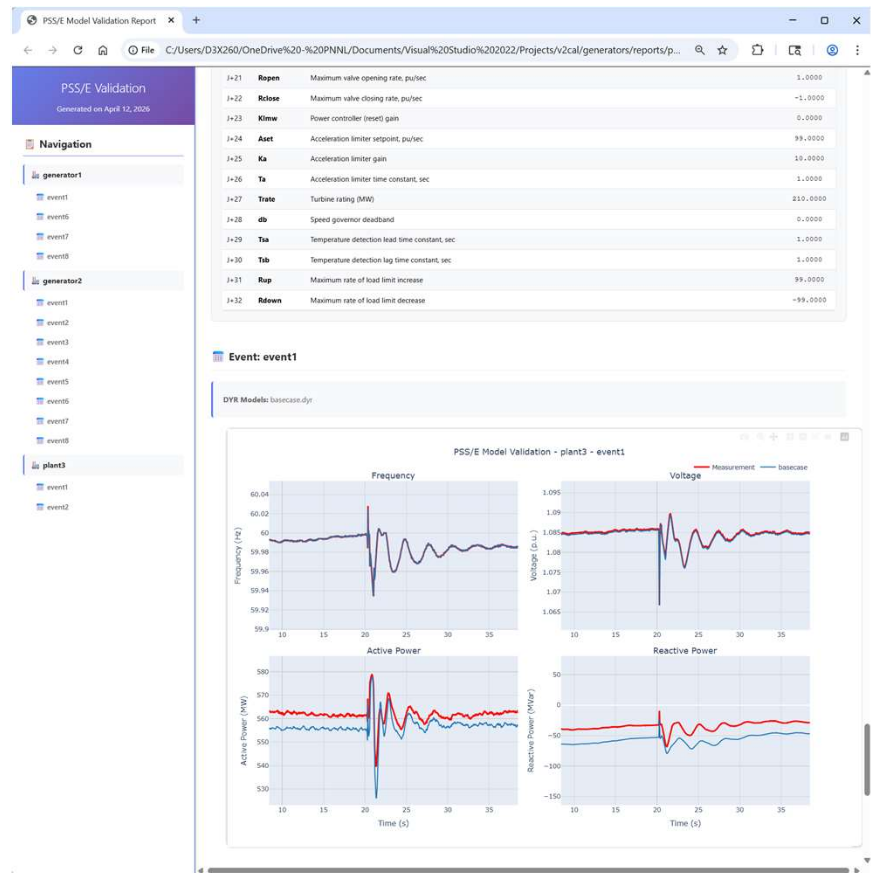
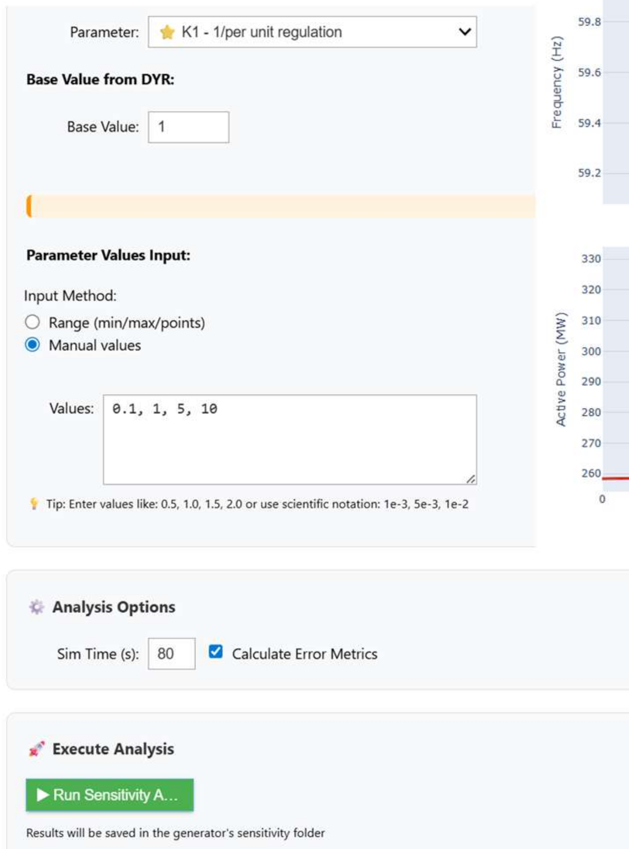
# Reporting & Visualization

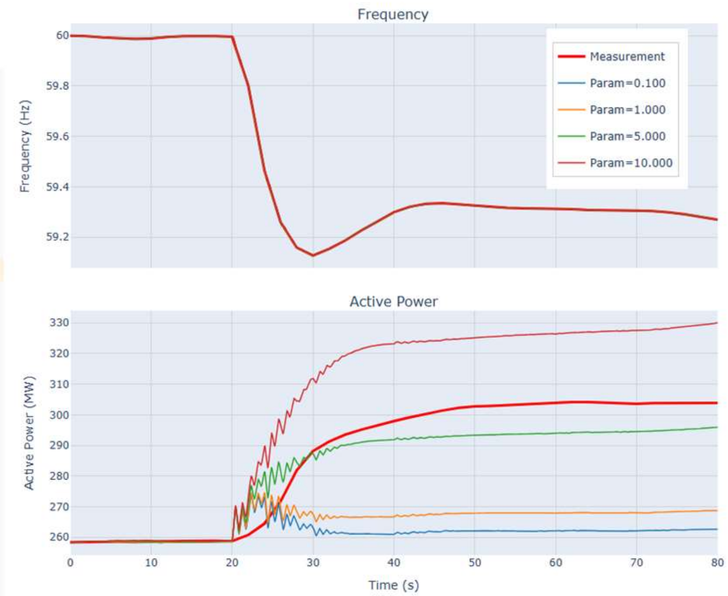
- Generates interactive HTML-based report
- Highly configurable (plots, tables, navigation structure, content selection)
- Supports interactive plots for deeper exploration of system behavior
- Provides tables with model parameters – no need to check dyr files
- Enables easy comparison of model responses — different parameter sets, before/after calibration



# Sensitivity Analysis

- Quantifies which model parameters most strongly influence active or reactive power control behavior
- Helps identify the most impactful parameters for pre-screening prior to calibration
- Supports understanding of model dynamics and control-loop behavior



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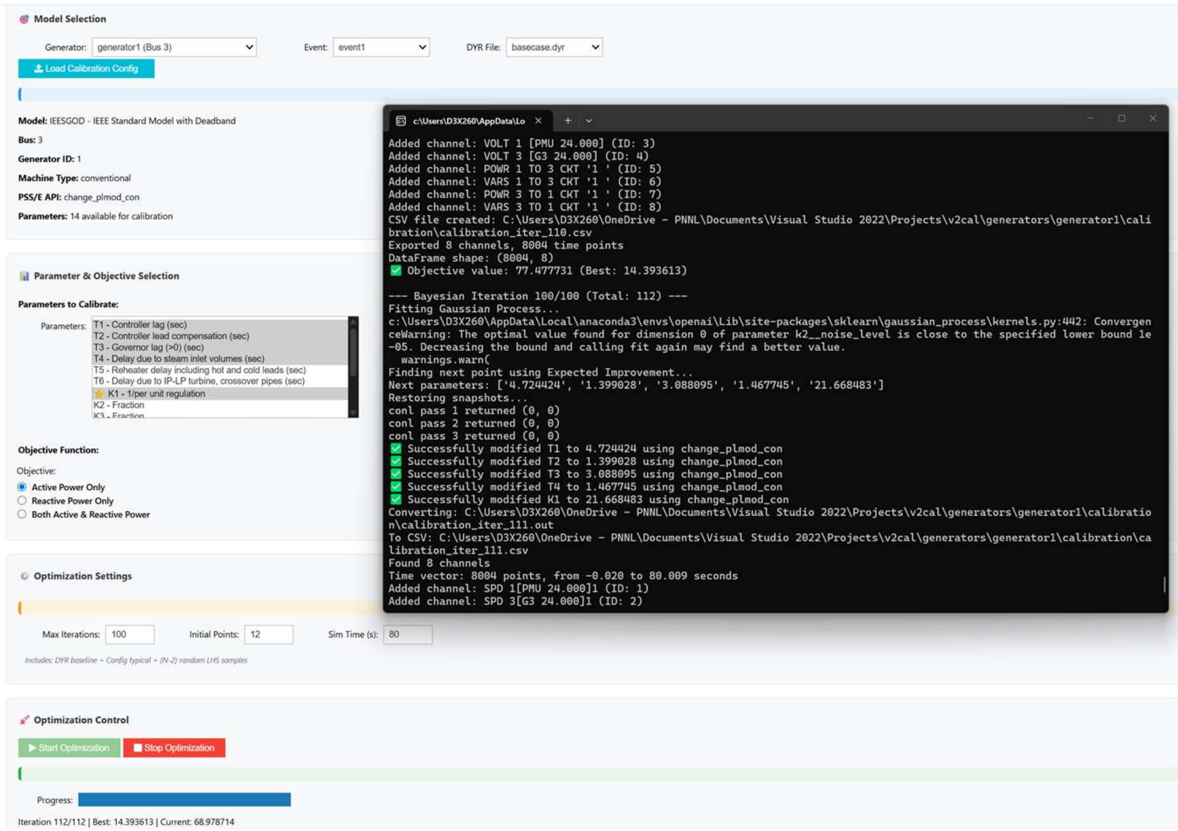
# Model Calibration

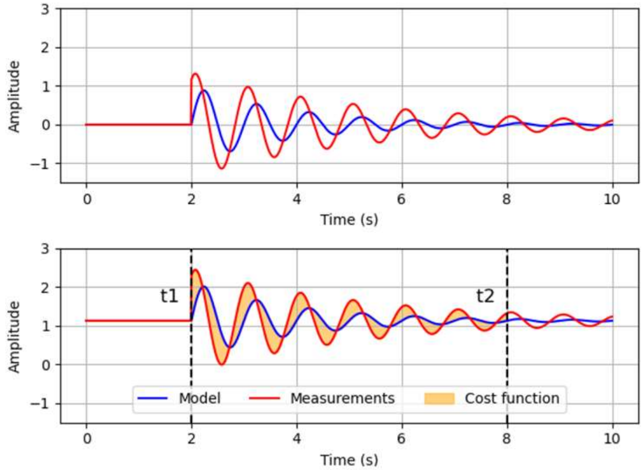
- Bayesian optimization automatically tunes model parameters to minimize mismatch between measured and simulated responses
- User selects which parameters to calibrate
- Flexible objective setup: optimize for active power (P), reactive power (Q), or combined P&Q performance



# Error metric

$$err(\boldsymbol{x})_{t_1}^{t_2} = \left| \int_{t_1}^{t_2} \left[ M_1(\boldsymbol{x}) - \min\left(M_1(\boldsymbol{x})_{t_1}^{t_2}, M_2(\boldsymbol{x})_{t_1}^{t_2}\right) \right] dt - \int_{t_1}^{t_2} \left[ M_2(\boldsymbol{x}) - \min\left(M_1(\boldsymbol{x})_{t_1}^{t_2}, M_2(\boldsymbol{x})_{t_1}^{t_2}\right) \right] dt \right|,$$

where *err(x)* expresses the mismatch between two time series $M_1$(observed response) and $M_2$(model-based response) in the time range $(t_1, t_2)$.




- This metric allows comparing signals with different temporal resolution and captures system response characteristics around a disturbance (e.g. rate of change, over/undershoot, settling values) without focusing solely on the sample-to-sample mismatch.

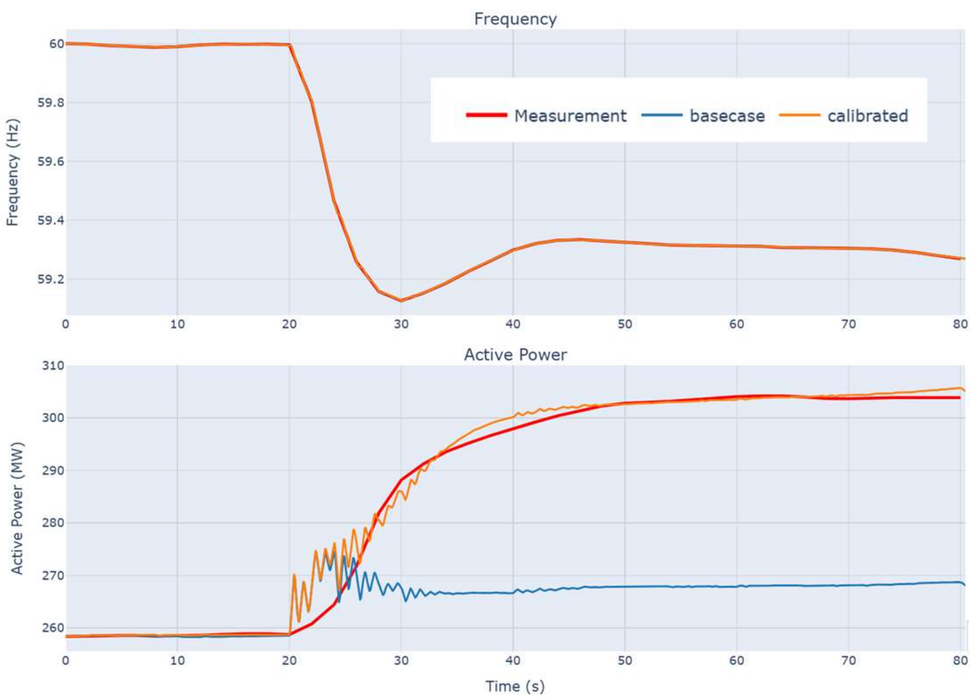
# Calibration based on Bayesian optimization approach

- **Bayesian Optimization (BO)** is a constrained, derivative-free optimization method.
  - Ideal for cost functions that are computationally expensive or lack analytical forms.
  - Uses a **Gaussian process surrogate model** to approximate the cost function.
  - Strategically selects new evaluation points based on prior observations to efficiently find global optima.
  - Bayesian Optimization package was used: https://github.com/bayesian-optimization/BayesianOptimization
- **Parameter Grouping Strategy:**
  - Parameters divided into groups based on their influence on DER behaviors.
    - ✓ Active power-frequency response parameters.
    - ✓ Reactive power-voltage response parameters.
- **Iterative Optimization Process:**
  - Calibrate parameters in one group using Bayesian Optimization, holding other groups constant.
  - Optimized parameters from one iteration inform the next iteration.
  - Process continues iteratively until no significant improvement in cost function is achieved.
- **Benefits of this Method:**
  - Reduces the number of costly simulations.
  - Efficiently identifies optimal parameter sets.
  - Systematically captures interactions between parameter groups for improved model accuracy.

**Algorithm 1** Iterative Parameter Calibration

**initialize** $n_g$: no. of parameter groups, $n$: iteration counter, $N$: max. no. of iterations, $\mathbf{x_0}$: initial parameter estimates, $\sigma$: tolerance threshold
$n \leftarrow 1$, $\mathbf{x}^* \leftarrow \mathbf{x_0}$
**while** $n \leq N$ **do**
  **for** $i = 1$ **to** $n_g$ **step** $1$ **do**
    Calibrate parameters in group $i$ using BO keeping all other parameters fixed to obtain parameters $\mathbf{x_n}$
  **end for**
  Evaluate cost function $f(\mathbf{x_n})$
  **if** $n > 1$ **then**
    **if** $f(\mathbf{x_{n-1}}) - f(\mathbf{x_n}) \leq \sigma$ **then**
      break
    **else** $f^* \leftarrow f(\mathbf{x_n}), \mathbf{x}^* \leftarrow \mathbf{x_n}, n \leftarrow n+1$
    **end if**
  **end if**
**end while**
**return** $\mathbf{x}^*$

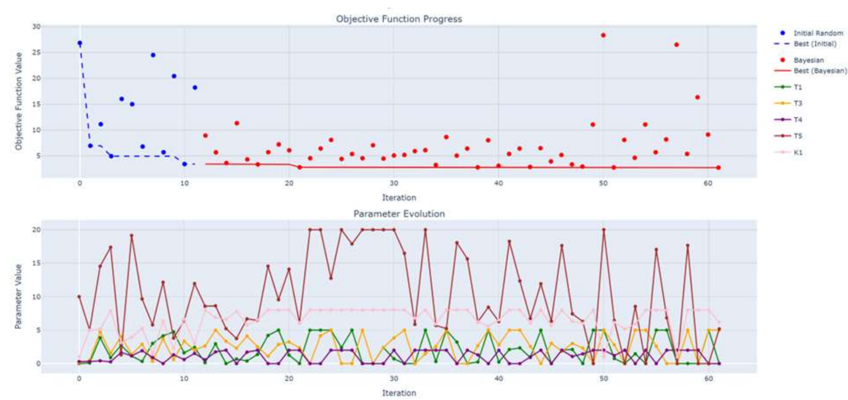
# Calibration Results



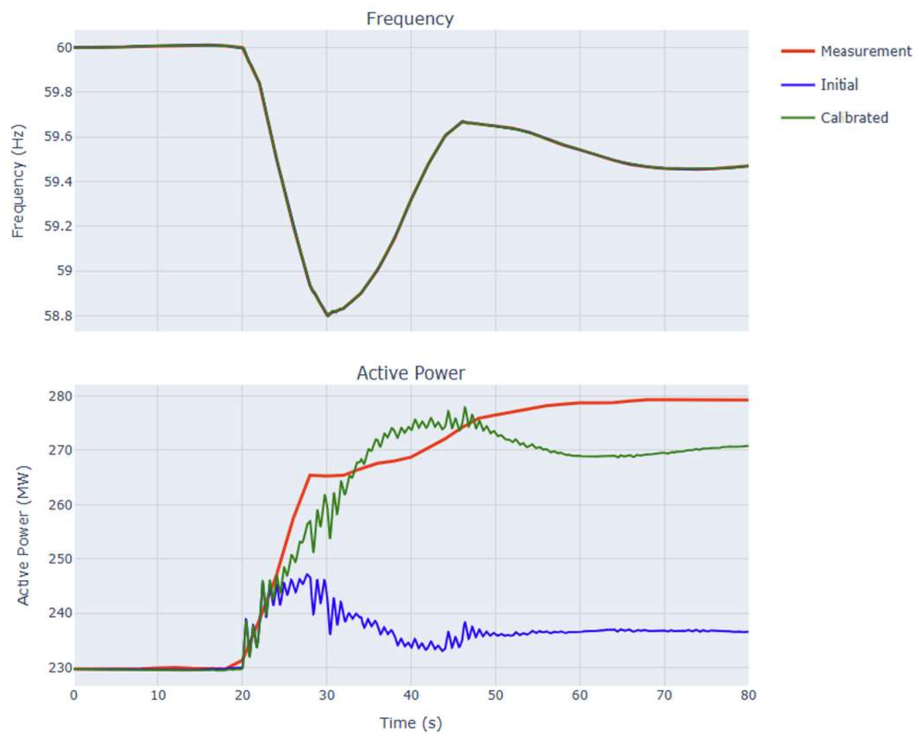

**Speed Governor Model Parameters**

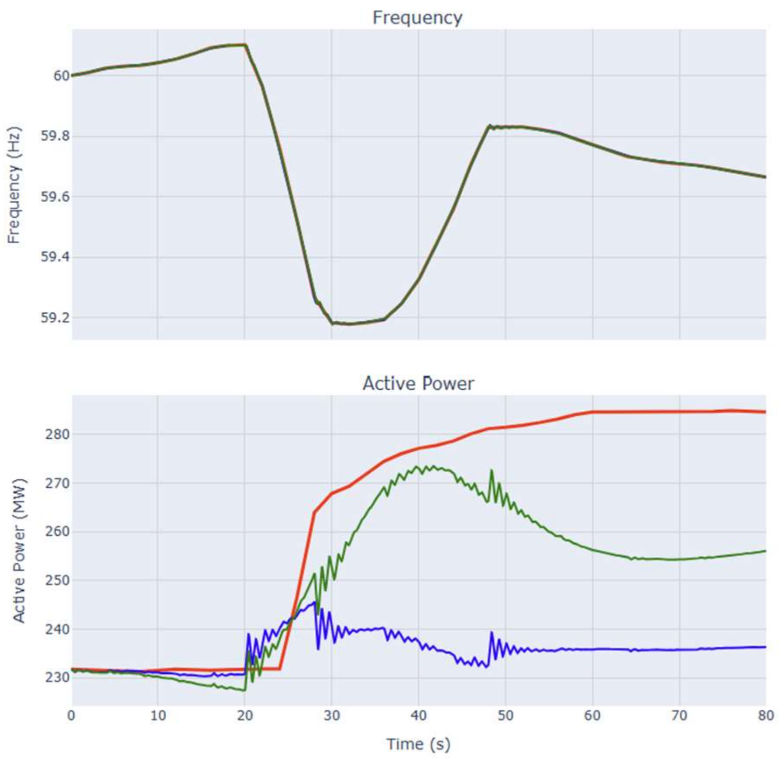
**Model:** IEESGOD - IEEE Standard Model with Deadband
**Bus:** 3

| Index | Parameter | Description | basecase | calibrated |
|---|---|---|---|---|
| J | T1 | Controller lag (sec) | 0.0000 | 1.0000 |
| J+1 | T2 | Controller lead compensation (sec) | 0.0000 | 0.0000 |
| J+2 | T3 | Governor lag (>0) (sec) | 0.1000 | 1.0000 |
| J+3 | T4 | Delay due to steam inlet volumes (sec) | 0.3000 | 1.0000 |
| J+4 | T5 | Reheater delay including hot and cold leads (sec) | 10.0000 | 10.0000 |
| J+5 | T6 | Delay due to IP-LP turbine, crossover pipes (sec) | 0.4000 | 1.0000 |
| J+6 | K1 | 1/per unit regulation | 1.000000 | 6.500000 |
| J+7 | K2 | Fraction | 0.7140 | 0.7140 |
| J+8 | K3 | Fraction | 0.6000 | 0.6000 |
| J+9 | PMAX | Upper power limit | 1.0000 | 1.0000 |
| J+10 | PMIN | Lower power limit | 0.0000 | 0.0000 |
| J+11 | DBH | Deadband for overspeed, p.u. | 0.0000 | 0.0000 |
| J+12 | DBL | Deadband for underspeed, p.u. | 0.0000 | 0.0000 |
| J+13 | Trate | Turbine rating, if zero, then MBASE used | 0.0000 | 0.0000 |



# Calibration results validation



# Future Work / Work in Progress

- Enable V²Cal for agentic workflows
  - Expose V²Cal capabilities through an MCP-compatible interface
  - Make the tool agent-friendly for automated orchestration
  - Support natural-language prompts for
    - ✓ Understanding model structure and parameters
    - ✓ Generating reports
    - ✓ Executing commands and analysis steps
- Extended simulation capabilities
  - Add support for EMT-level simulation tools (e.g., PSCAD)
  - Perform EMT-based model validation
  - Benchmark and compare RMS vs. EMT model behavior for consistency and fidelity

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# Conclusion

- $V^2$Cal streamlines end-to-end measurement-based model validation through a fully automated workflow
- Integrates data ingestion, play-in case construction, simulation, sensitivity analysis, and parameter calibration
- Bayesian optimization and targeted parameter selection improve model fidelity while minimizing analyst effort
- Interactive HTML reports enhance transparency, traceability, and collaboration
- Overall, $V^2$Cal accelerates verification workflows and supports more reliable active and reactive power control modeling

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# Thank you