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HILL with Integration Tool in RE-INTEGRATE : Experience and Its Learnings

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U.S. DEPARTMENT
of **ENERGY**

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EMT Initiative

Bring together national labs, academia, and industry partners under one platform to accelerate the development and use of electromagnetic transient (EMT) simulation software.



NATIONAL LABS



ACADEMIA



INDUSTRY



Vision

Enable **industry's transition** to EMT simulation for a secure, reliable future grid through an ecosystem.



Overall Goal

Integrate models, data, validation, standards, and workforce training.

IMPACT • NEAR-TERM



Faster interconnection studies



Reliable deployment of large loads and new generation



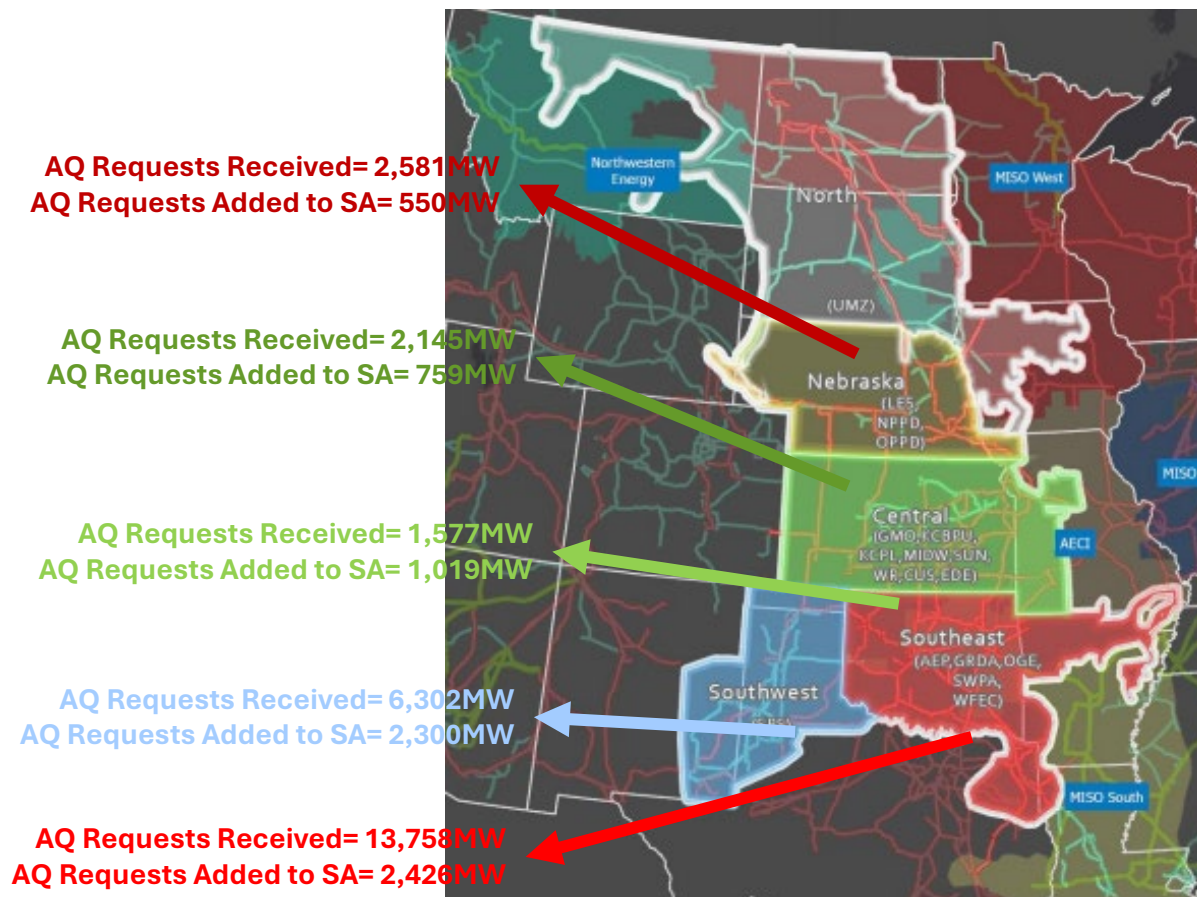
Higher **return on capital** and **lower capital** expenditure

Overview

- High Impact Large Loads (HILL) Impact in SPP region.
- RE-INTEGRATE Simulator
- Integration Tool with RE-INTEGRATE
- Demonstration
- User Experience

SPP Attachment AQ and loads (≥ 100 MW) (ISD: 2021-2027)

SPP loads of 100 MW or greater include a variety of types, such as battery storage, cryptocurrency and AI facilities, data centers, gas compressors, industrial parks, municipal loads, pumping stations, retail, and wind-related loads. However, most large load requests have not disclosed their specific load type.



Why Do HILLs Matter to SPP?

Impact on Transmission Planning

- HILLs can require new transmission infrastructure or upgrades

Grid Reliability

- Sudden or concentrated load growth can affect system stability and operational reliability

Resource Adequacy

- High-demand loads may influence the need for additional generation or capacity planning

Congestion and Power Flows

- HILLs can shift power flows and increase congestion in specific areas

Market Impacts

- They can influence locational marginal pricing (LMPs), Operating Reserves, and overall market dynamics

Timing and Uncertainty

- Many HILL projects come with uncertain timelines or undisclosed details, complicating planning

High Impact Large Load

Definition

- A new commercial or industrial load, or increase in commercial or industrial load, at a single site connected through one or more shared Points of Interconnection (POIs) or delivery points

MW Threshold

- Less than or equal to 69 kV: Greater than or equal to 10 MW
- Greater than 69 kV: Greater than or equal to 50 MW

Exclude

- Electric Storage Resource

Requirements

- Register in Market
- Evaluated by existing Tariff study processes and under new supplemental study processes
- SPP Ride-through Requirements Compliance

Perform within 90 Calendar Days

- Steady state, short circuit, and Transient Stability considering SPP HILL ride through requirements
- Electromagnetic Transient (EMT) Screening includes Short-Circuit Ratio and Critical Clearing Time (SCRCCT) screening
- Note: If issues occur, perform full EMT analysis

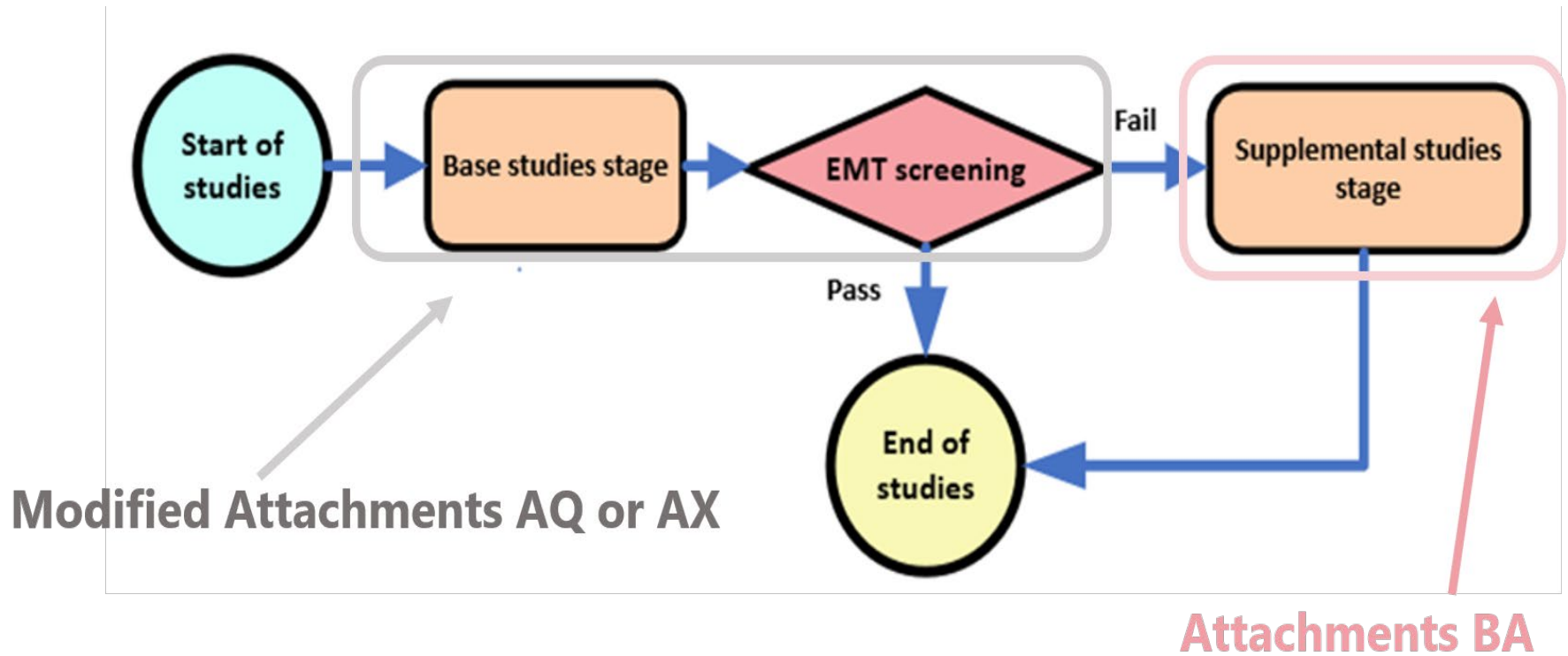
Applicability

Applicable only to new HILLs

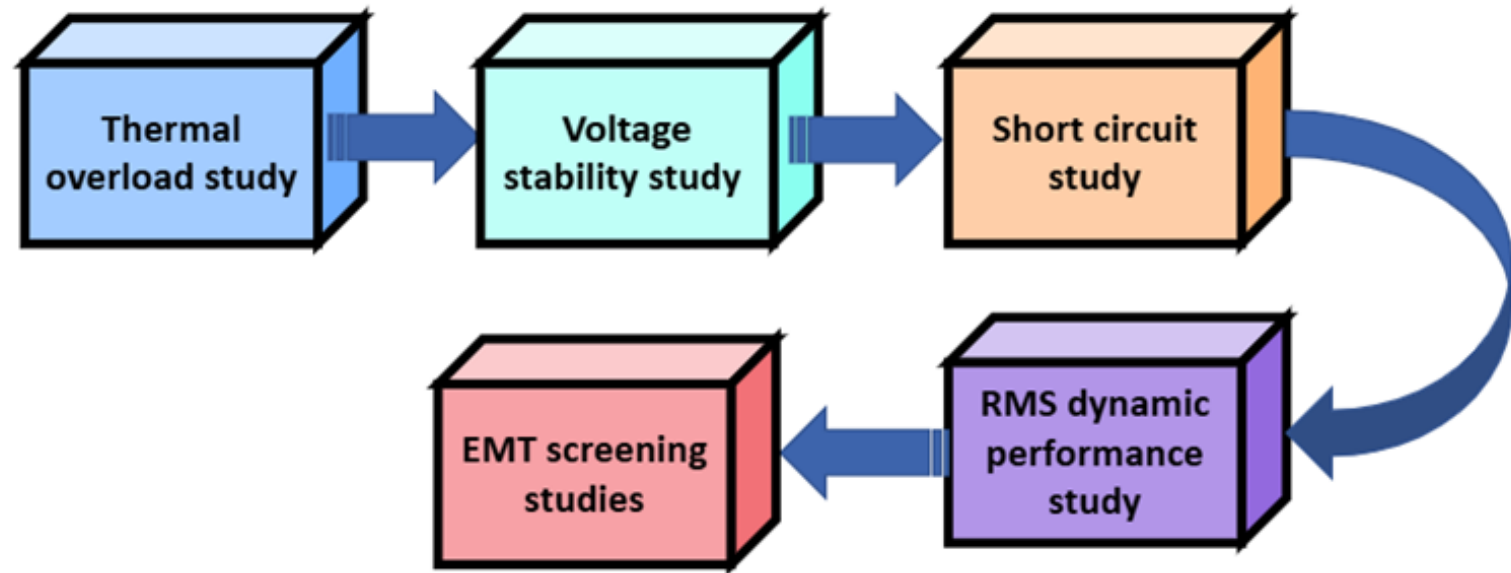
- The requirements set forth in this document shall apply exclusively to HILLs submitting interconnection requests through SPP's transmission service process or HILLs being supported by a High Impact Large Load Generating Facility on or after **January 15, 2026¹**.
- HILLs with interconnection requests submitted to Transmission Owners **prior** to Effective Date shall make reasonable efforts within capabilities of their facilities to maximize ride-through performance and provide documentation outlining such efforts upon request.

1- Notwithstanding any other provision, the requirements set forth herein may apply solely to the power-electronic portion of a HILL, provided the HILL Delivery Point Study ("HDPS") demonstrates that such an exemption will not adversely affect the reliability of the SPP Grid. For illustrative purposes, where a HILL has a total capacity of 50 MW, of which 45 MW constitutes conventional industrial load without a power-electronic interface, and 5 MW constitutes power-electronic-based load, these requirements shall apply exclusively to the 5 MW power-electronic portion of the HILL and not to the remaining 45 MW.

RECOMMENDED HDPS STUDIES



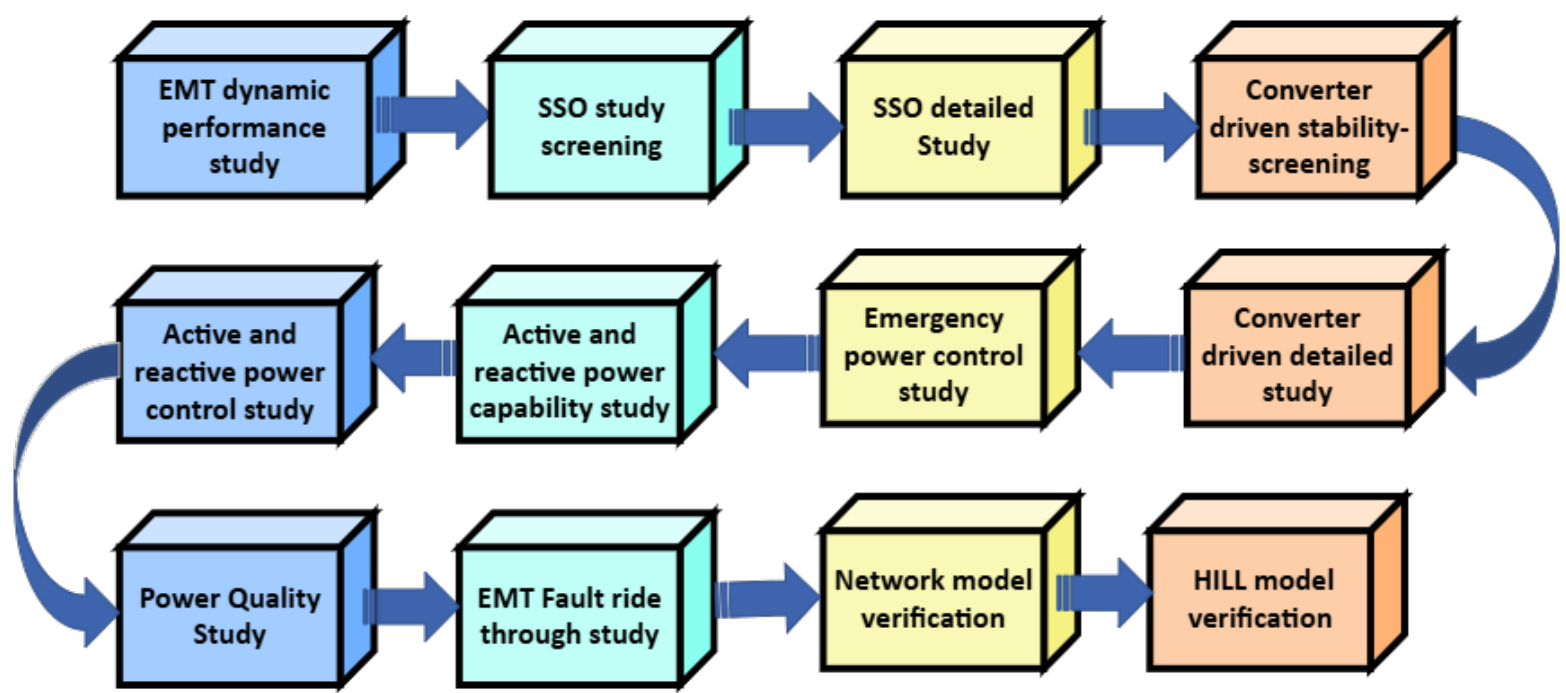
Base Studies Stage



EMT screening

- **Screening thresholds:** identify weak/unstable interconnection points.
- **SCR, WSCR, CSCR < 3.0** = electrically weak → higher risk of voltage/control instability.
- **CCT < 0.15s** = system may not withstand common fault durations → transient stability risk.
- **If thresholds not met (SCR/WSCR/CSCR < 3.0 or CCT < 0.15s):** detailed studies (e.g., EMT simulations) are required.

Supplemental Studies Stage (Integration Process with EMT)





Integration Process with RE-INTEGRATE



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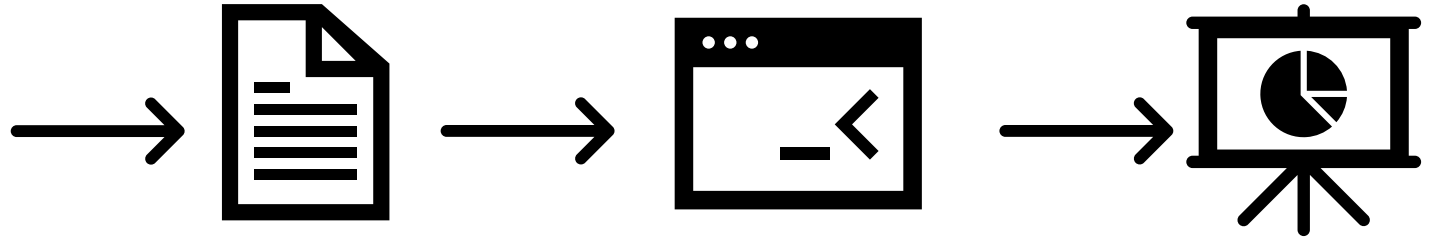
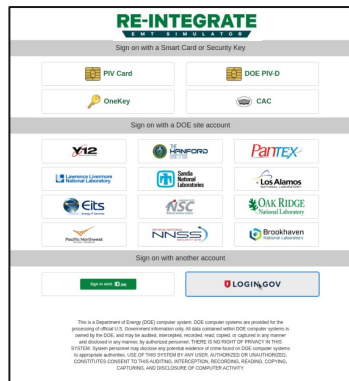
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RE-INTEGRATE

E M T S I M U L A T O R

RE-INTEGRATE EMT Simulator



Authentication

- Access control
- Secure interface
- Secure Storage

Cases

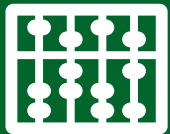
- Typical use formats (RAW, DYR, DSS, ..)
- Built-in Parsers

EMT Simulation

- Intelligent Matrix reordering
- Multiple Solvers.

Results

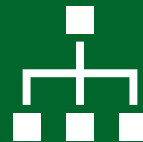
- Time-domain waveforms.
- Reports & Analytics.



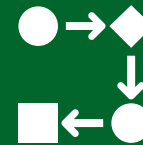
**Advance
Solvers**



**Detailed
Model Library**



**Parallel
Processing**



**Automated
Workflows**



**AI
Enabled**

RE-INTEGRATE EMT Simulation: Current Capabilities



Characteristics	RE-INTEGRATE
Solvers	RE-INTEGRATE's structure-aware solvers (BD, BBD, BTD*), hybrid integrators (ImEx), KLU, SuperLU (mixed-precision), intelligence to select solvers/integrators Multicore/GPU-compatible
Input Data Structures	.raw, .dyr, .dss, .xml, .fau, .seq, .json
Component Models	Generation (synchronous) + exciters + governors + PSS, HVDC, transmission lines, transformers, loads, inverters, large loads – ~100+ models available
Simulation Speed	•Real-time with IEEE 39-bus with 375 inverter system (demonstrated at workshop) •Speed-up of differing magnitudes with existing software (multiple publications) •Latest benchmark: Speed-up (cumulative) of 240x observed
Largest System Tested	118,000 bus (millions of nodes) 125,000 inverters
Test Systems Examples	IEEE 9-bus, 10-bus, IEEE 39-bus , IEEE 118-bus, IEEE 123-bus, ActivSg200-bus, 234-bus, 390-bus, 1180-bus, 3900-bus, 11800-bus, 39000-bus, 118000-bus, real-world systems (3) – 25+ systems
Features	Contingency selection , grid strength analysis, LLM integration (with partners)
Applications	MQT, RT, Integration tool

Long-Term Research Goal: Simulate 10+ million nodes with 1+ million inverters in near real-time

Target: Plug-and-play approach to perform interoperable research on individual modules with ease of usage, allaying tools, standard models/data structures, advanced integrators/solvers, AI-infused capabilities for large-scale studies

Integration Tool with RE-INTEGRATE

- **What is Integration Tool?**

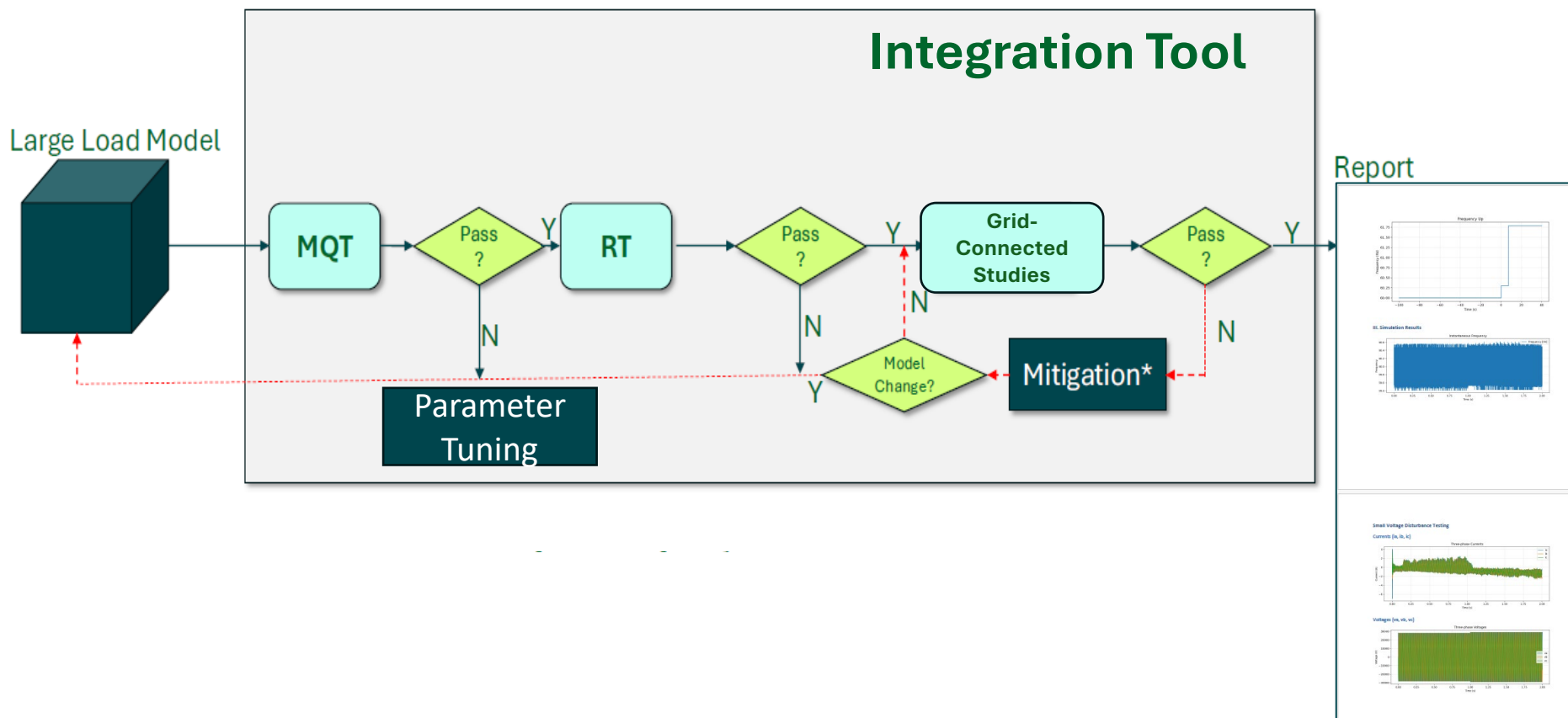
The Integration Tool is an automated simulation framework powered by our in-house EMT engine, **RE-INTEGRATE**, specifically engineered to standardize model quality testing (MQT) and ride-through (RT) compliance, while seamlessly extending high-fidelity EMT analysis to large-scale, bulk power grid-connected studies.

- **Capabilities of the Integration Tool:**

- **End-to-end test flow in one environment.** MQT, RT, and grid-connected testing share one engine, one model, and one data path, with no re-building or re-translating between stages.
- **Automated test execution.** Standard test batch can run in sequentially.
- **Objective evaluation.** Simulation results presented in report format for human validation.
- **Bulk power system integration.** The tested model connects to network representations for further grid-connected tests.

* Recently tested Integration Tool with SPP network connecting data center model.

Integration Tool with RE-INTEGRATE for Large Load



Model Quality Tests (MQT)

There is no single, universally accepted, “formal” definition of EMT model quality, but industry guidelines (e.g., NERC, SPP) describe it in terms of accuracy, completeness, and validation against real-world performance. A concise definition could be the following:

“EMT model quality refers to the degree to which an EMT model accurately represents the physical and control behavior of power system components under fast transient conditions, ensuring fidelity across all relevant scenarios and validation against measured or benchmarked data.”

Example MQT Test list,

- Flat Start Steady-State
- Small Voltage Disturbance Test
- Small Frequency Disturbance Test
- Short Circuit Ratio (SCR) Grid Strength Sweep
- Phase Angle Change Test

1. NERC, “Reliability Guideline Electromagnetic Transient Modeling for BPS Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices,” March 2023.
2. SPP, “SPP Electromagnetic Transient (EMT) Model Requirements for Inverter-Based Resource Interconnection,” Revision 1, March 10, 2023.

```
"MQT" :
{
  "Individual" :
  {
    "Component1" :
    {
      "ModelPath" : "/host/input_files/Interconnection/IBLParams.xml",
      "Parameters" :
      {
        "IBLConverter:IBL_hardware:R2ac_0hm" : [1.0e-3, 2.0e-3],
        "IBLConverter:IBL_software:Kp_Q" : [0.3, 0.1]
      }
    }
  },
  "Functional" :
  {
    "Model" :
    {
      "Plant" : "/host/input_files/Interconnection/components12Feeders.dss",
      "Generic" :
      {
        "IBLConverter" : "/host/input_files/Interconnection/IBLParams.xml"
      },
      "OEH" :
      {
        "IBL1" : "/host/input_files/Interconnection/IBLParams.xml"
      }
    },
    "Test":
    {
      "Flat Start" :
      {
        "vmag" : 1.0,
        "phase" : 0,
        "frequency" : 60,
        "duration" : 5
      },
      "Small voltage disturbance" :
      {
        "increase" :
        {
          "at" : 1,
          "percent" : 3,
          "duration" : 5
        },
        "decrease" :
        {
          "at" : 1,
          "percent" : 3,
          "duration" : 5
        }
      },
      "Phase angle jump test" :
      {
        "origin" : 1,
        "jump" : 1,
        "at" : 1,
        "duration" : 5
      },
      "Grid strength" :
      {
        "SCR" : [10, 8, 7, 3, 1],

```

Implement Model Quality Testing in RE-INTEGRATE EMT Simulation Platform

Running Model Quality Testing



Please wait...

Ride-through Requirement (RTR) Tests

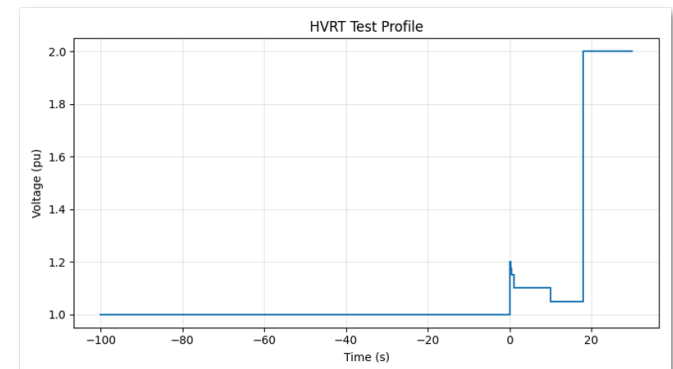
Ride-through is the ability to withstand voltage or frequency disturbances inside defined limits and to continue operating as specified (IEEE Std 2800-2022).

This capability helps prevent widespread blackouts, maintain grid stability, and ensure continuity by allowing systems to endure the disturbance for a short period of time.

Types of ride-through:

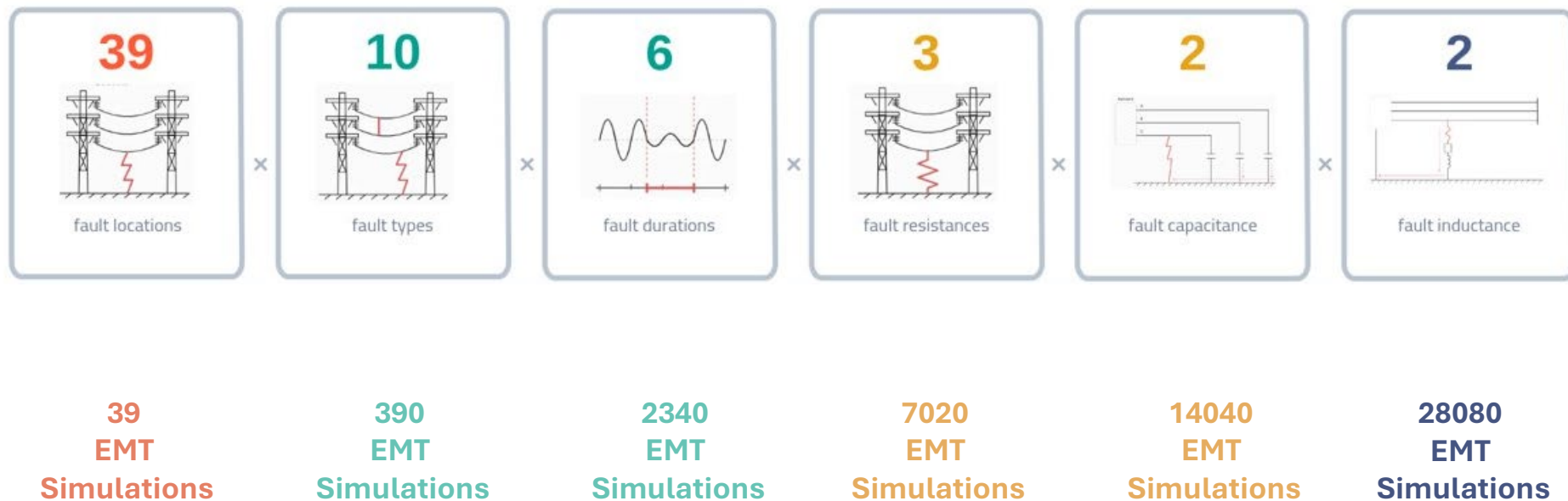
- **Fault ride-through:** Ability to withstand temporary voltage and frequency deviations during grid faults.
- **Low-voltage ride-through:** Ability to withstand temporary voltage sags during disturbances.
- **High-voltage ride-through:** Ability to withstand temporary high-voltage conditions during disturbances.
- **Frequency ride-through:** Ability to withstand frequency deviations outside of normal limits during disturbances.

```
"Ride-through" :  
{  
  "Voltage ride through" :  
  {  
    "profile" : ["/host/input_files/Interconnection/profile_LVRT.txt",  
                 "/host/input_files/Interconnection/profile_HVRT.txt"  
    ],  
  },  
  "Frequency ride through" :  
  {  
    "profile" : ["/host/input_files/Interconnection/profile_HzUP.txt"]  
  }  
}
```

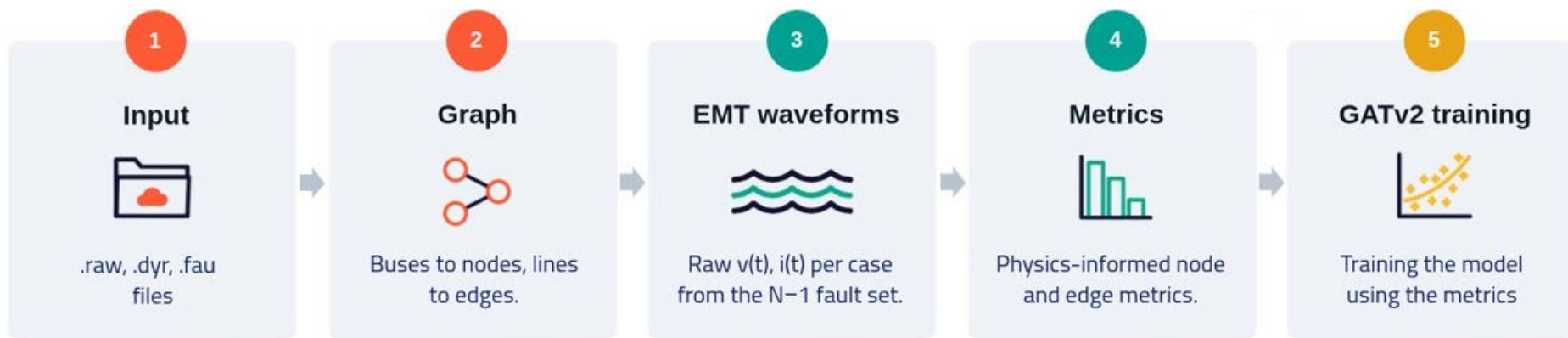


Contingency Selection. Why?

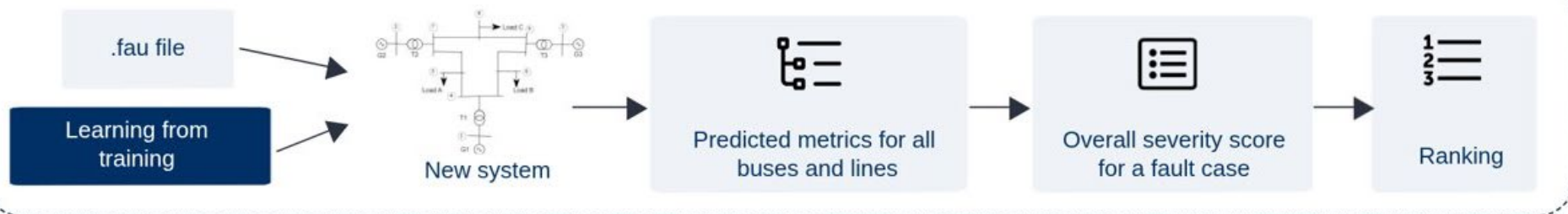
For the IEEE 39-bus system, each unique combination of fault and fault parameters is executed as one EMT simulation.



Contingency Selection Process



Contingency selection



Analysis Report

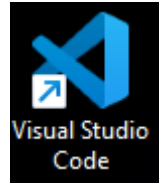
Requirement or criterion	Applicability condition	Plot evidence	Outcome	Citation(s)
Controlling interconnection requirements and POI voltage limits: No facility-specific SPP/transmission-owner voltage limits or controlling agreement are supplied.	Establish the executed agreement, applicable tariff revision, transmission owner, and study/event date before assigning requirements.	No POI voltage measurement or verified current measurement location.	INDETERMINATE	No facility-specific controlling provision is present in the supplied excerpts.
Voltage ride-through: R1 requires ride-through within the Attachment 1 "must Ride-through" zone, subject to its stated exceptions. The supplied material does not include the voltage-band thresholds and durations in Tables 1 and 2.	Confirm PRC-029-1 applicability, obtain the missing tables, and evaluate any claimed exception using event evidence.	Current changes alone do not establish voltage-zone entry, duration, disconnection, or an exception.	INDETERMINATE	[prc-029-1.pdf p. 2]; [prc-029-1.pdf p. 13]
Voltage measurement and duration accounting: Applicable voltage is the maximum/minimum phase-to-neutral or phase-to-phase fundamental RMS voltage at the main-transformer high side. Relevant voltage-band durations are accumulated within any 10-second period. Tables 1 and 2 apply only when frequency is within the specified must-ride-through zone.	Confirm the measurement point, RMS processing, voltage base, applicable tables, and concurrent frequency.	The approximate 1-second current contraction cannot substitute for accumulated voltage-band durations.	INDETERMINATE	[prc-029-1.pdf p. 13]
Frequency ride-through: Attachment 2 specifies continuous operation from 58.8 through 61.2 Hz , 299-second requirements for the adjacent frequency bands, and "may trip" regions above 61.8 Hz and below 57.0 Hz . Durations are cumulative within 10 minutes.	Confirm PRC-029-1 applicability and use high-side frequency measurements with the stated measurement processing.	No frequency record; the 30-second current image does not establish the required cumulative history.	INDETERMINATE	[prc-029-1.pdf p. 14]
R3 frequency-event condition: Ride-through is required within the Attachment 2 must-ride-through zone when absolute RoCoF is ≤ 5 Hz/s , unless a documented R4 hardware limitation exists. RoCoF is averaged over at least 0.1 s and is not calculated during fault occurrence and clearance.	Establish applicable frequency conditions, event boundaries, and any documented hardware limitation.	No numerical frequency, RoCoF, or fault timing is available.	INDETERMINATE	[prc-029-1.pdf p. 4]

Integration Tool Demo

User Experience -Pros VS Cons

- Report
- Pass/Fail
- Process Documentation on set up procedure
- On-Boarding
- Future Potential

- Visual Studios
- “Coding”
- Local Access to RE-INTEGRATE



These are being addressed using UI

- IT/Cyber Security Concerns – Case by Case



PE
Components

6 PROJECTS



PE Sub-
systems

5 PROJECTS



Grids

24 PROJECTS



PEs + Grids

5 PROJECTS



Confidential
Real Systems

2 PROJECTS

Thank You!

Acknowledgement: The authors thank U.S. Department of Energy (DOE) Office of Electricity (OE) Advanced Grid Modeling (AGM) and the EMT initiative for their invaluable guidance and kind support in this work!

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Model Quality: Who Should Do What?

Description	Who should do it
Contractual terms and conditions needed to prepare EMT models (e.g., with OEMs)	GOs
Create and enforce EMT model requirements	TPs and PCs
Cross-platform benchmarking of models (e.g., benchmark against PSS®E)	OEMs, with requirements from GOs
Review cross-platform benchmarking	TPs and PCs
Quantifiable screening studies	TPs and PCs
Conform with EMT model requirements	GOs and OEMs

Description	Who should do the testing		
	Developing model	Testing model	Submitted to
Individual models	OEMs	GOs (creates E-MQA)	TPs
Entire facility or plant	GOs (help from OEMs)	GOs (creates P-MQA)	TPs

- Original Equipment Manufacturers: OEMs
- Transmission Planners: TPs
- Planning Coordinators: PCs
- Generation Owners: GOs
- PSS®E: Power System Simulator for Engineering

1. NERC, “Reliability Guideline Electromagnetic Transient Modeling for BPS Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices,” March 2023.

MQT and RTR,

- **Model Quality Testing (MQT)** is an **administrative and structural gatekeeper check**. Its primary purpose is to prove that your model is mathematically stable, does not crash the grid operator's simulation software, and accurately represents the physical equipment. It answers the question: *"Is this model mathematically healthy enough to be used in grid studies?"*
- **Ride-Through Testing** is a **functional performance check**. Its purpose is to prove that the facility can survive electrical emergencies (like lightning strikes or sudden voltage drops) without tripping off the grid. It answers the question: *"Can this asset physically survive a grid disturbance?"*

interconnection package to a grid operator (like ERCOT or CAISO), **ride-through simulations are embedded directly within the MQT test suite checklist.**

*"SPP's materials focus on plant-level dynamic response requirements... plus a **Dynamic Model Quality & Performance Test report**... The proposal **enumerates a model-quality test menu**: initialization checks, **balanced fault ride-through**, small V/F disturbances, **HVRT/LVRT**, **HFRT/LFRT**, protection verification, and an SCR sweep." [1]*

1. <https://www.tomscaramellino.com/post/spp-and-miso-ibr-modeling-compliance-how-to-deliver-study-grade-udms-now-and-validate-to-as-built-later>SPP, "SPP Electromagnetic Transient (EMT) Model Requirements for Inverter-Based Resource Interconnection," Revision 1, March 10, 2023.

Contingency Selection and Study

Transfer Learning for Contingency Selection

- Learn on the small system or a subpart of bigger system, apply to the large one or with different operating condition.
- Attention normalized within each node's own neighborhood. Physics-informed loss acts as a prior that carries over.
- Severity ordering moves to a new system with a small fine-tuning set instead of bulk simulation.

Metrics that Carry Across Different Operating Conditions

- They are computed on EMT domain, so nothing is filtered before measurement.
- Self-referenced, dimensionless, size-independent and value means the same thing on any systems or operating conditions.
- Transfer degrades gracefully with distribution shift rather than breaking because the label means something different.

Focused Analysis

- The screener produces an ordering, and the cut-off produces a working set.
- Probability aware selection: A contingency that occurs once in fifty years does not compete with one that occurs several times a year.
- Each retained case carries its own explanation: which metric drove it, which propagation path the attention map indicates.

Contingency Selection Metrics

NODE LEVEL · SEVEN PER BUS

- **Voltage depression energy** area of the sag over the window
- **Voltage violation duration** time spent outside the band
- **Voltage recovery time** how long to return
- **Peak instantaneous voltage** highest excursion during the fault
- **Steepest dv/dt** fastest instantaneous change
- **Frequency nadir** lowest frequency reached
- **RoCoF** rate of change of frequency

EDGE LEVEL · THREE PER LINE

- **Current-deviation integral** per phase, referenced to pre-fault
- **First-2-cycle overcurrent** per-unit, inrush window
- **Residual overcurrent** per-unit, rest of the window

WHY THESE

- Dimensionless by construction, no units to reconcile.
- Self-referenced denominators, never ensemble statistics.