Reliability and Resilience Webinar Series Topic One Part Two: Remedial Action Scheme Design, Coordination and Modeling

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Project Background

- The U.S. Department of State, Bureau of Energy Resources, Power Sector Program (PSP) provides technical and regulatory support to the Central American regional electricity market.

- Under the PSP, Pacific Northwest National Laboratory delivers technical and analytic support to Ente Operador Regional (EOR, the Central American regional system operator).

Presentation Outline

Part 1 (April 14th, 2021)

- Introduction
- Standards and Practices in North America
- Overview of RAS Design Principles
- Coordination and Review Process Example from North America

Part 2 (April 21st, 2021)

- Questions from the Part 1
- RAS Modeling Approaches for Operational Security Studies
- Deep Dive on RAS Modeling in PSS/E
- Ideas for Applications to Central America

Topics from Part 1

- Standards and Practices in North America
- Overview of RAS Design Principles
- Coordination and Review Process Example from North America

Questions from RAS Session 1

- Regarding the technical criteria used, are they consistent throughout the USA or are different criteria used to design and coordinate RAS? *- Emily*
- If there are different criteria, how do you reach consensus or agreement to know which ones to apply when the RAS involves areas with different criteria? *- Emily*
- How are technical controversies resolved between areas when an associated RAS does not have the performance or effects that are desirable for all? *- Emily*
- How much time, on average, does it take in the USA to design, coordinate, test and implement a RAS? *- Xiaoyuan*
- Can the evaluation of the performance of the RAS (ECS), be evaluated before 5 years? For example, if it is evident that in the face of contingencies it has a conflict with other RAS or its effects and parameters of its adjustments are not adequate with the characteristics that occur in the events or contingencies that it intends to mitigate? *- Juan Carlos*
- Are RAS audits performed? *- Answered in Part 1*
- Who makes up the RAS entity? *- Answered in Part 1*

Questions from RAS Session 1

- What are the most appropriate communication protocols or standards used in the North American system for ECS data acquisition? *- Xiaoyuan*
- When does a RAS become unnecessary? Can they be eternal or should planning evaluate an alternate solution in the long term? *- Emily*
- Who approves the scheduled maintenance of elements that are part of a RAS? *- Xiaoyuan*
- Who absorbs the cost of a RAS in the event that it is requested by an RC or RAS entity? *- Xiaoyuan, Juan Carlos*
- How often are full tests of RAS performed and how are they coordinated when involving multiple areas? *- Juan Carlos*
- Are systemic protection schemes part of RAS, considering that the monitored variables are located in different geographic areas? *- Juan Carlos*

Additional resources:
Western Interconnection RAS Review: https://www.wecc.org/Reliability/Western%20Interconnection%20RAS%20Review%20Guideline.pdf
Reliability Coordinator and Planning Coordinator NERC Reliability Standard PRC-012-2 Process Document for Eastern Interconnect: https://www.spp.org/documents/62226/spp%20prc-012-2%20process%20ei.pdf

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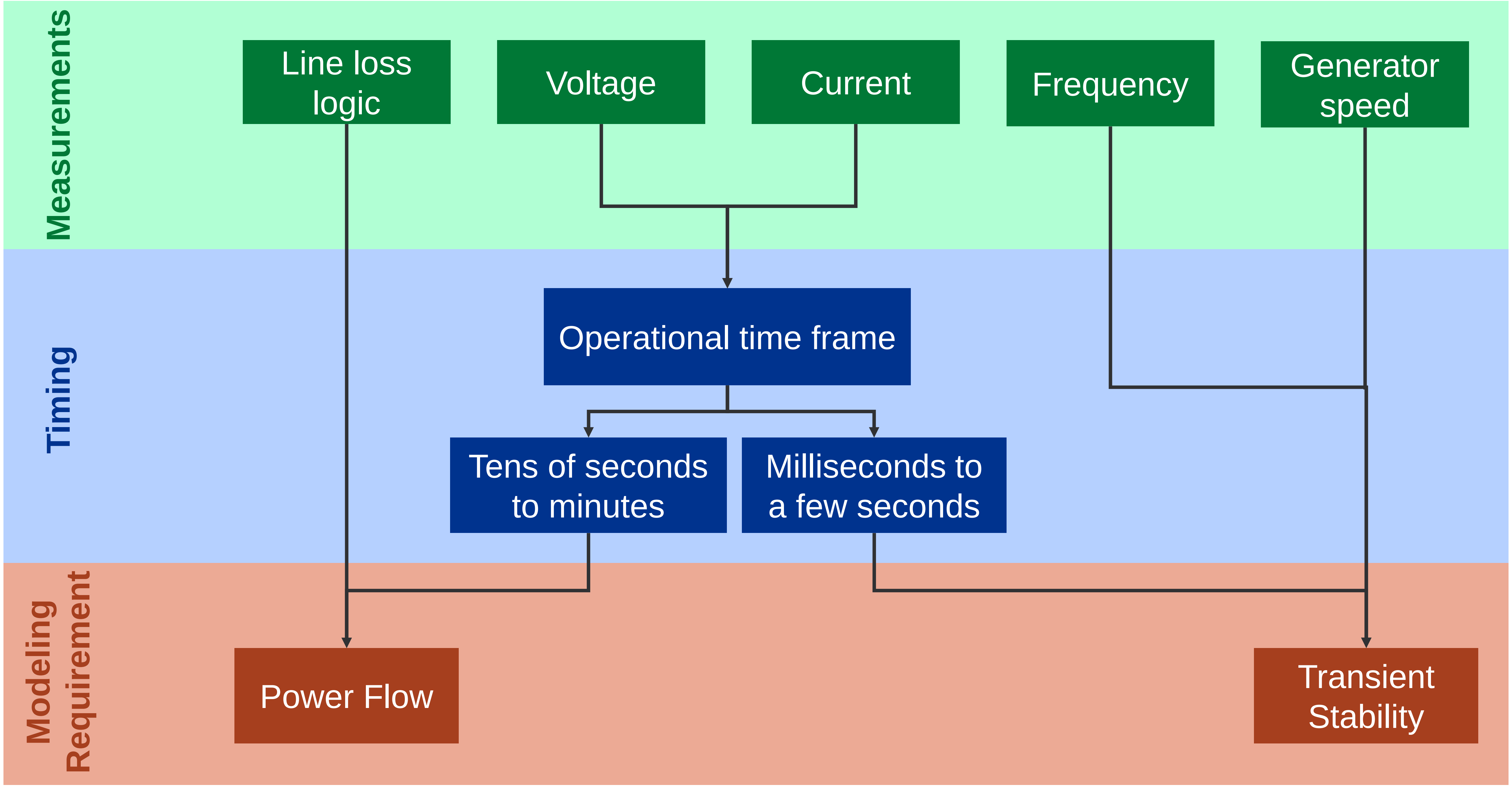
RAS Modeling Approaches for Operational Security Studies

Modeling Considerations for RAS



Some Common Approaches for Modeling RAS in Contingency Analysis

- **Manually:** Engineer manually applies the remedial action that they know will occur based on contingencies and conditions in the base case.
- **When analyzing results:** Based on previous studies and engineering experience, filter out any results of contingency studies that would be resolved by RAS.
- **Using custom scripts:** Engineer automates one or both of the previous processes using custom code.
- **Using contingency definitions in a power flow solver:** Using filters and conditional contingency actions, implement RAS as custom contingency.

Manual Application of RAS: Pros & Cons

Advantages

- Does not require additional software or computer-readable models
- May support both transient and steady state models

Disadvantages

- Time-intensive
- Introduces additional opportunities for human error
- Difficult to do for complex RAS
- Reproducibility
- Knowledge transfer

Result Filtering: Pros & Cons

Advantages

- Does not require additional software or computer-readable models
- May support both transient and steady state models

Disadvantages

- Time-intensive
- Introduces additional opportunities for human error
- Difficult to do for complex RAS
- Reproducibility
- Knowledge transfer
- As the system changes over time, studies may not catch if RAS no longer mitigates all violations

Custom Scripts: Pros & Cons

Advantages

- Faster than manual approaches
- Better reproducibility than manual approaches
- May support both transient and steady state models

Disadvantages

- Difficult to do for complex RAS
- Scripts must be maintained
- For scripts that do result filtering, similar problems arise around verifying that the RAS continues to resolve all violations as the system changes over time

Using Custom Contingencies: Pros & Cons

Advantages

- Faster than manual approaches
- Better reproducibility than manual approaches
- Easier to maintain than custom scripts
- Where standards exist and common tools are used, can be shared with other entities

Disadvantages

- Contingency definitions can be complex
- Requires training and/or knowledge of how to define custom conditional contingency and filters
- More difficult to do in transient stability studies

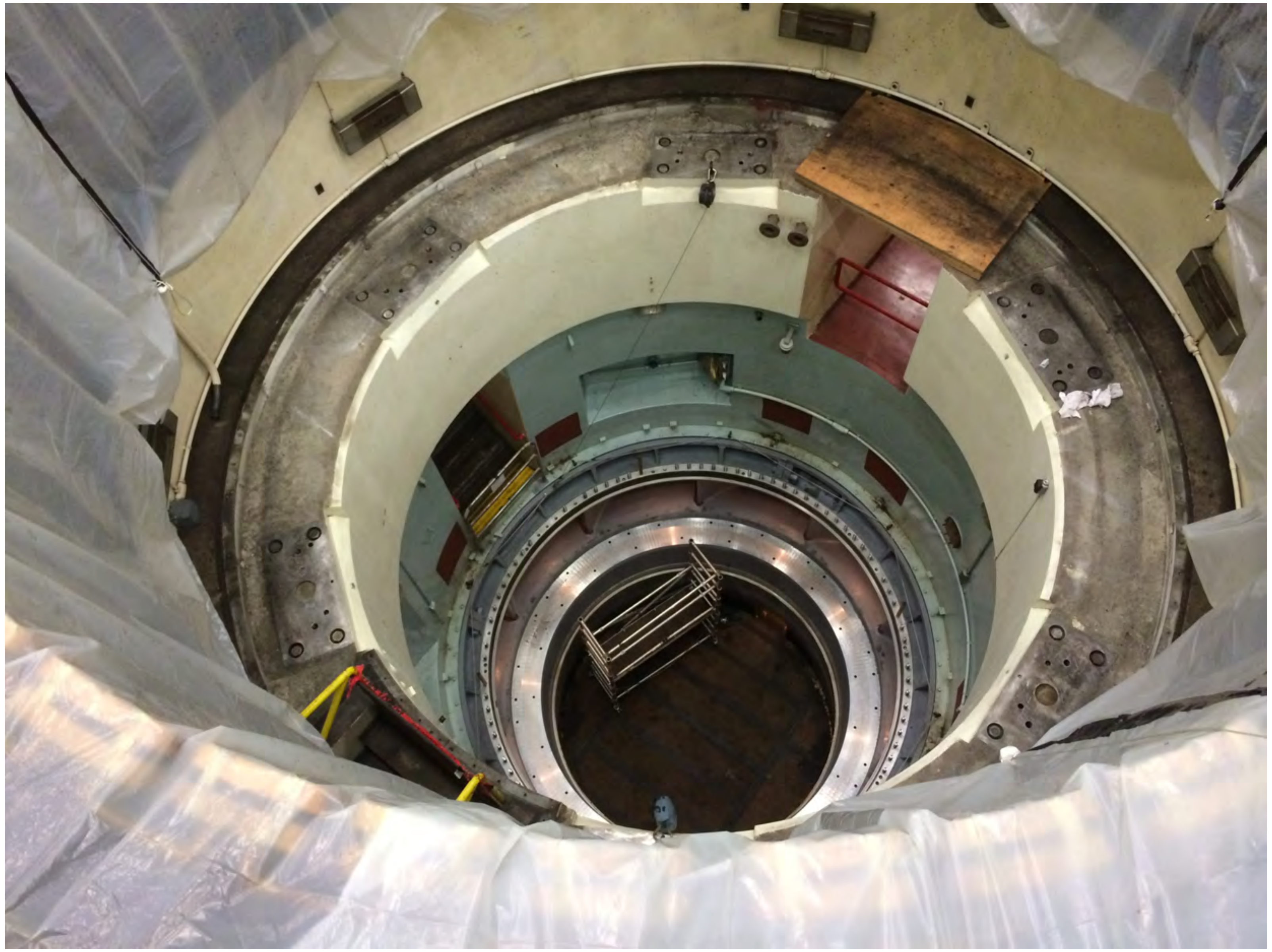
Survey of Practices for Modeling RAS in WECC

In 2017, PNNL conducted a survey among several WECC transmission operators to collect the following information on RAS and RAS modeling in the region:

- **Software** – The type of software used to perform power system analysis.
- **Objective** –The purpose of the RAS, specifically what the RAS is intended to protect against.
- **Remedial Actions** – The corrective actions taken.
- **Arming Criteria** – The monitored topology or system conditions used to set the arming levels for RAS implementation.
- **Initiating Conditions** – The monitored topology or system conditions that trigger the RAS to operate.
- **Modeling Method** – How the RAS is modeled in the software, including whether the RAS leverages existing software tools and whether transient analysis is performed.

Survey Results: RAS Objectives

- Prevent loss of synchronism
- Prevent line or transformer overloading
- Prevent generator damage
- Maintain voltage stability

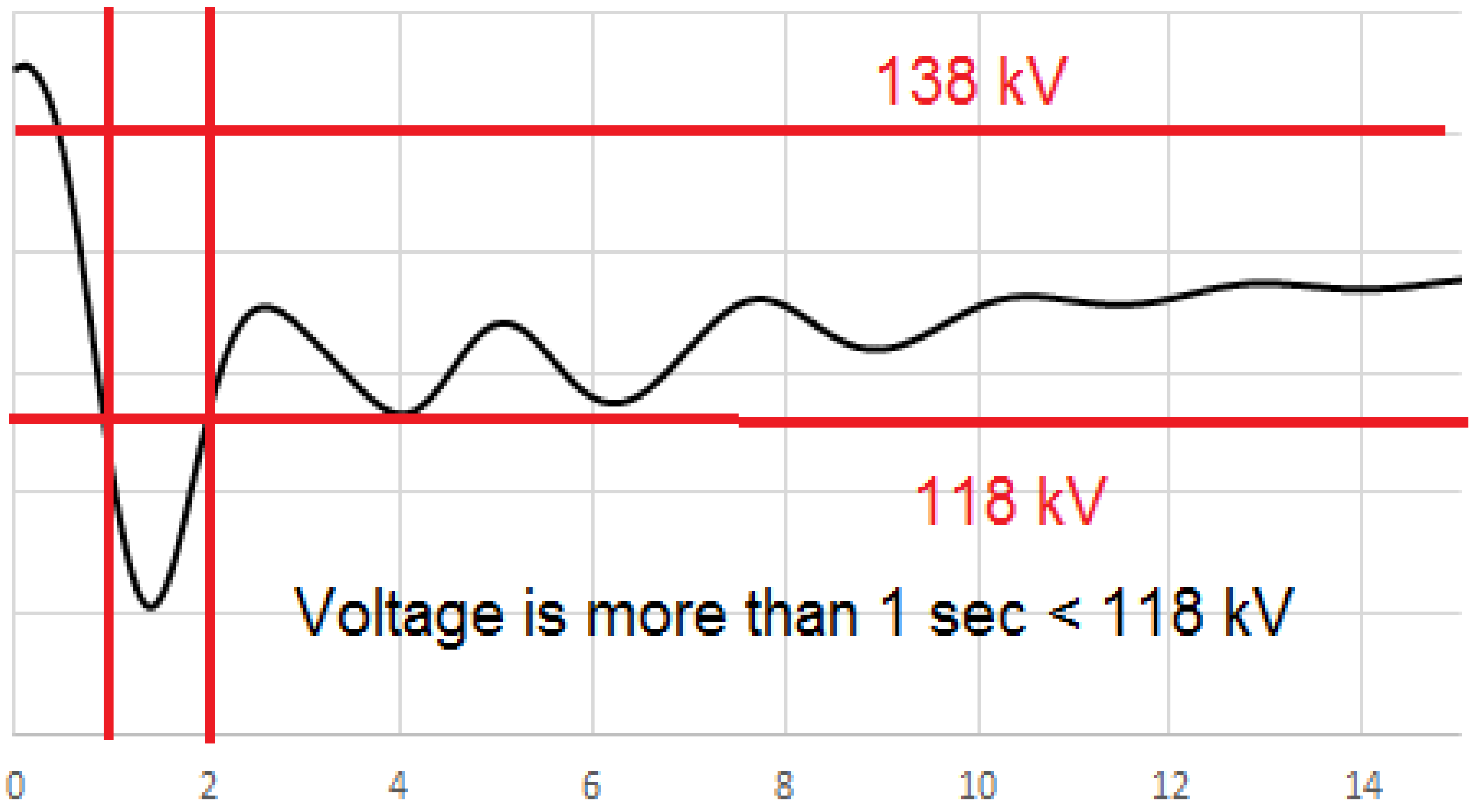


Survey Results: Arming Criteria

- Measured generation output
- Path flows
- Line or transformer flows
- Bus voltage

Survey Results: Triggering Criteria

- Line loss logic
- Generator acceleration
- Time elapsed since meeting arming criteria



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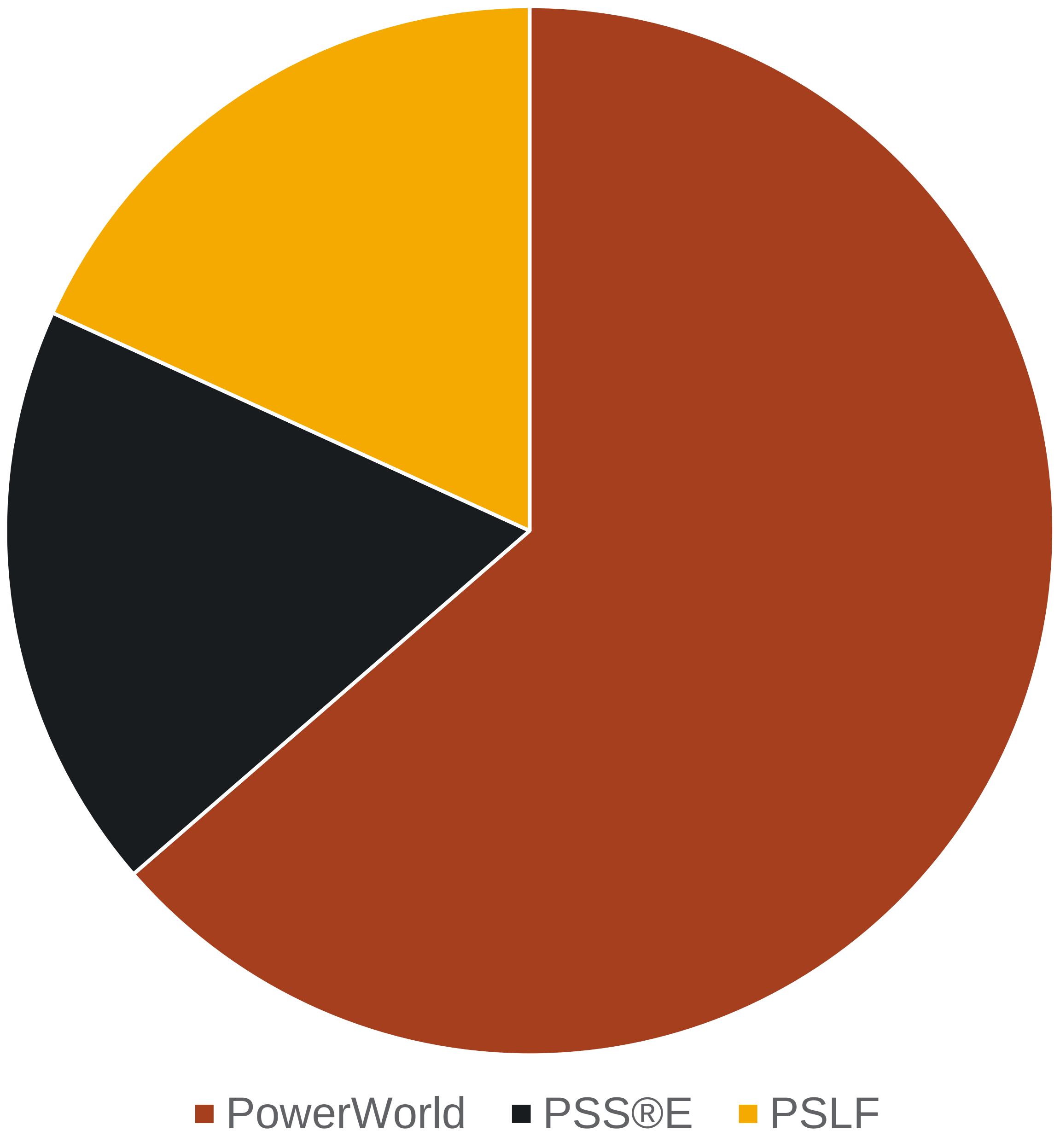
Survey Results: Remedial Actions

- Trip generator(s) offline
- Remove lines or transformers from service
- Reduce generation output
- Reconfigure shunt and series reactive power devices

Survey Results: Modeling Tools



Survey Results: Modeling Approaches

	PowerWorld	PSS®E	PSLF
Steady-State Power Flow	Most commonly modeled in WECC RAS & CTG format using built-in RAS tools	Most commonly manually implemented	Not commonly used for steady-state studies
Transient Stability	Most commonly included in contingency definition	Most commonly custom scripts are used	Most commonly included in the contingency definition, often with a custom EPCL

The Motivation for RAS Standardization in WECC

- 2011 San Diego blackout
  - Following the 2011 blackout, attention increased to studying RAS operation and understanding how RAS interact
- Need to incorporate RAS models into reliability studies
  - There are hundreds of RAS in WECC
  - Some RAS span multiple regions and impact multiple operating entities

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Modeling Approaches Leveraged in WECC

- Use **advanced filters** to identify if arming and triggering criteria are met (e.g., line flow > a prescribed threshold or limit)
- Define **conditional contingencies** which will point to advanced filters and apply contingencies/take actions if filter criteria are met
- Model generation drop using **injection group contingency actions** and disconnecting generators in merit order based on defined criteria
- Include defined conditional contingencies, which **represent RAS actions**, in operational security analyses
- WECC developed standards around the contingency definition and formats for RAS so that these files can be shared across the region

Additional Resources

- Modeling of RAS and Relays in Power Flow Contingency Analysis: https://www.powerworld.com/files/09WeberRAS_Features.pdf
- Modeling of Remedial Action Schemes and Relays in Power Flow Simulations: https://www.wecc.org/Reliability/RAS%20Modeling%20Webinar%20Presentation%204-2-2015.pdf
- Record Specification and File Format for Specifying Contingency Definitions and Remedial Action Schemes: https://www.wecc.org/Reliability/WECC_RASFileFormat_08-28-2015.pdf

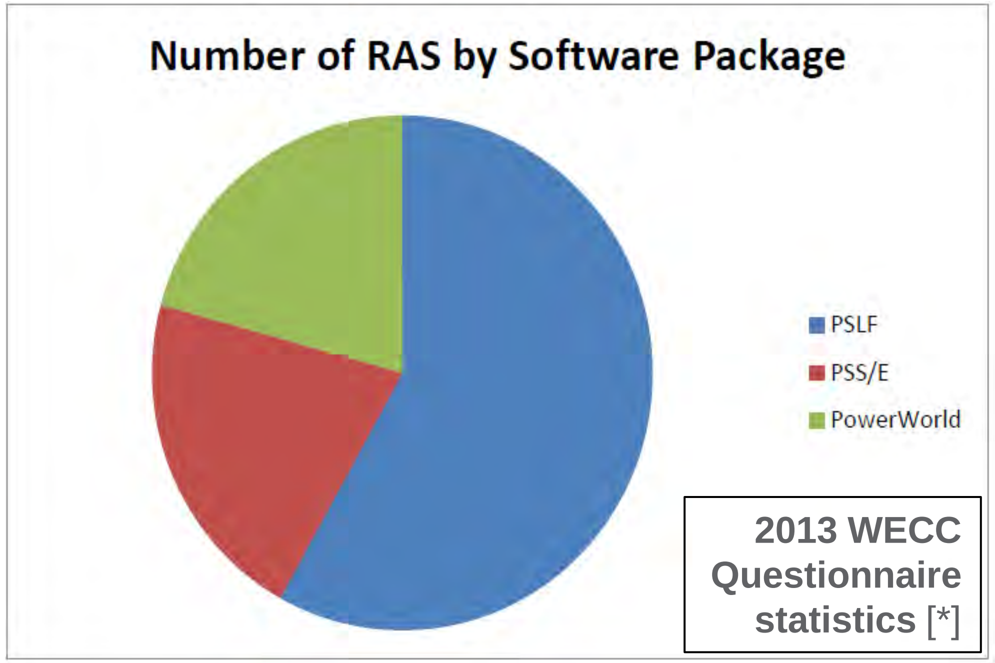
Survey of Central America RAS Survey Results

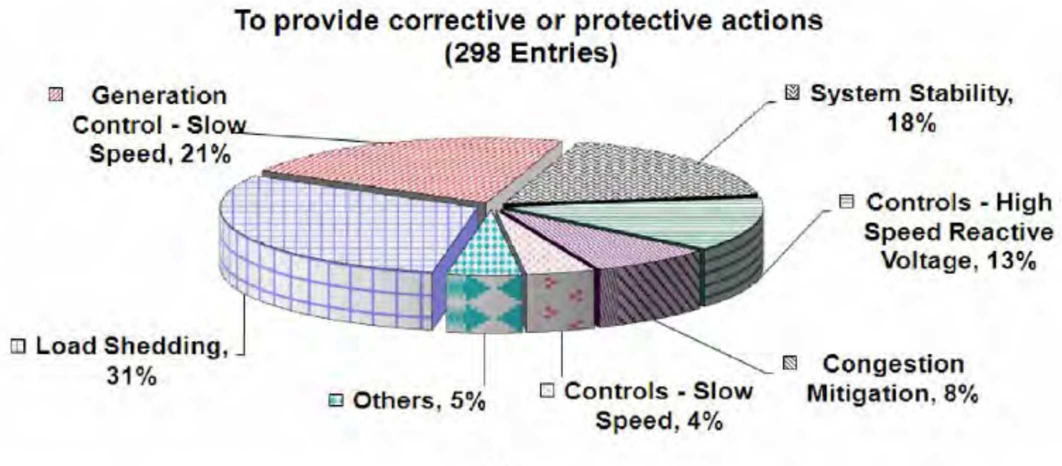
- Received 5 responses
- **Number of RAS:** Ranged from 0-33
- **Review Period:** Ranged from annual revision, six-months, to when changes in the system occur or RAS operation occurs.
- **RAS Modeling:** 2 include RAS in operational security studies
  - 1 entity uses PSS/E and python
  - 1 entity uses DSAT
- **Software limitations:**
  - PSS/E version
  - Line tripping in PSS/E based on frequency limit violations

Deep dive on RAS modeling in PSS/E

Review RAS Modeling in Commercial Software

- WECC distributed a questionnaire in 2013 to the Transmission Planners (TP), in which it also collected the modeling practice for RAS.
- IEEE Power System Relaying Committee (PSRC) completed a survey from 2005 to 2009, through the collective efforts with CIGRE and EPRI members.





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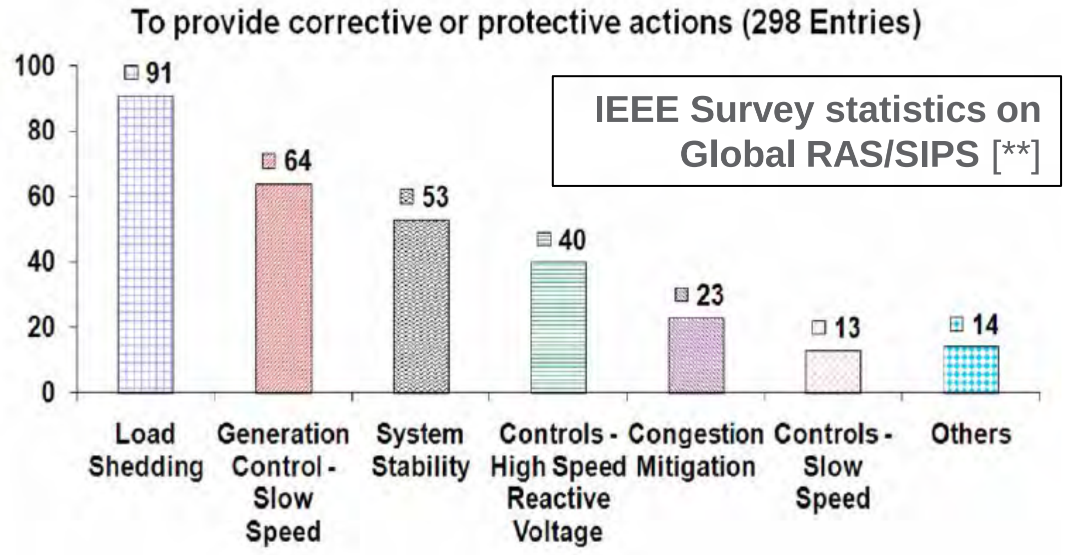


[*] WECC Technical Studies Subcommittee white paper, “Remedial Action Scheme (RAS) Modeling Value Proposition”, approved and published on May 2, 2014.
[**] V. Madani et al., "IEEE PSRC Report on Global Industry Experiences With System Integrity Protection Schemes (SIPS)," in IEEE Trans.on Power Delivery, vol. 25, no. 4, pp. 2143-2155, Oct. 2010.

Reference RAS Example in PSS/E

- Different commercial software have their own implementation and procedures for RAS modeling, including but not limited to, user interface function, customized coding API, interactive graphical portal, and so on.
- EOR and many Central American utility companies use PSS/E in transmission planning studies.
- For example, PSS/E V33.12 provides the capability of Python-based RAS API, and one testing example in the software package.
  - Python package “PSSRAS”
  - Flexible definition for customized RAS
    - Condition
    - Action
    - RAS definition (name)
  - Simulated within the PSS/E ACCC activities

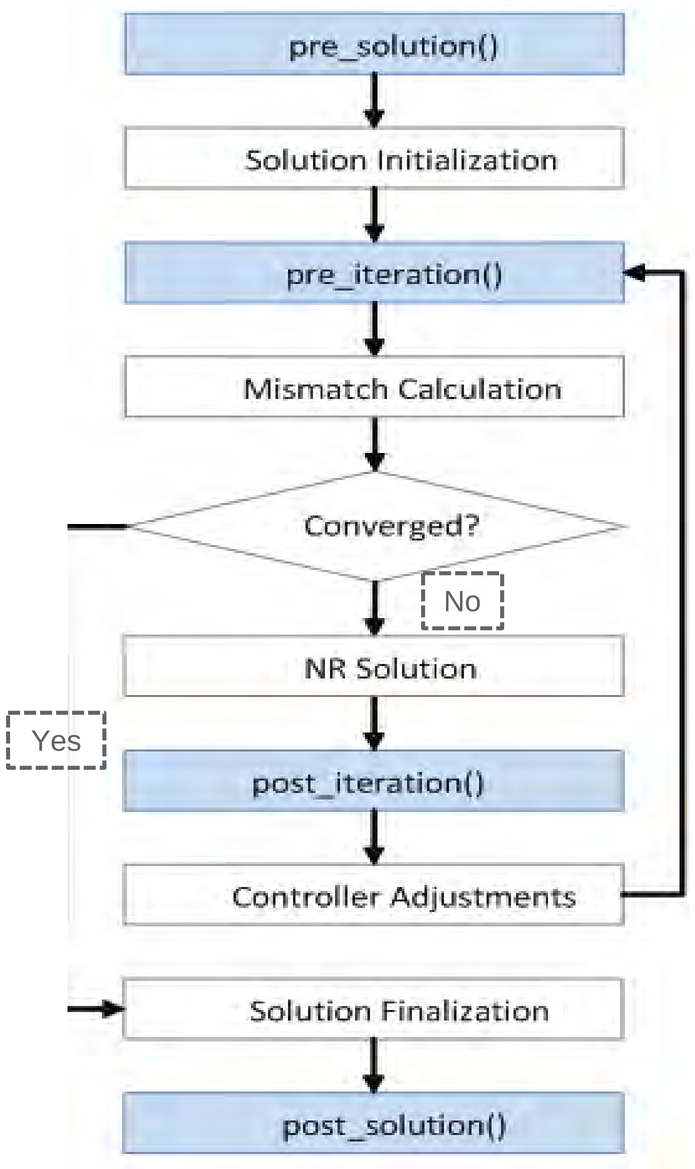
```
def  condition():
    a = branch_is_open(151, 152, 1)
    b = branch_is_open(151, 152, 2)
    c = bus_voltage(151) < 0.96
    return (a or b) and c

def action():
    open_branch(152, 202, 1)

define_ras(“RAS-1”, condition, action)
```

Sample python code [*]

[*] Siemens, PSS/E Advanced Contingency Analysis and RAS Module document, available online: https://assets.new.siemens.com/siemens/assets/api/uuid:13592114fa75914812edf89f7ed6f8849b23d63e/psse-advcontingencyanalysisandras-module-flyer.pdf

Modeling RAS in Steady-state Planning Study

- In power system steady-state planning study, power flow modification and control actions can be performed in an offline style, such as manual/code-based modification after N-1 contingency analysis.
    - In operational environment, if a RAS is not automated, the grid operator/dispatcher must watch the line flows and outage conditions, then arm and/or trigger the appropriate RAS
- PSS/E supports RAS definition and implementation in its contingency analysis

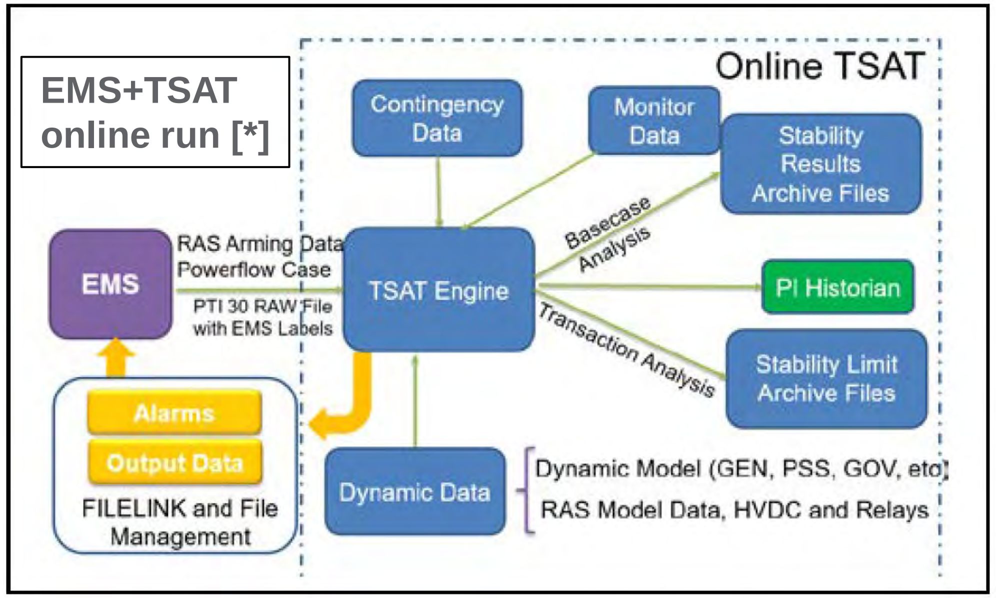


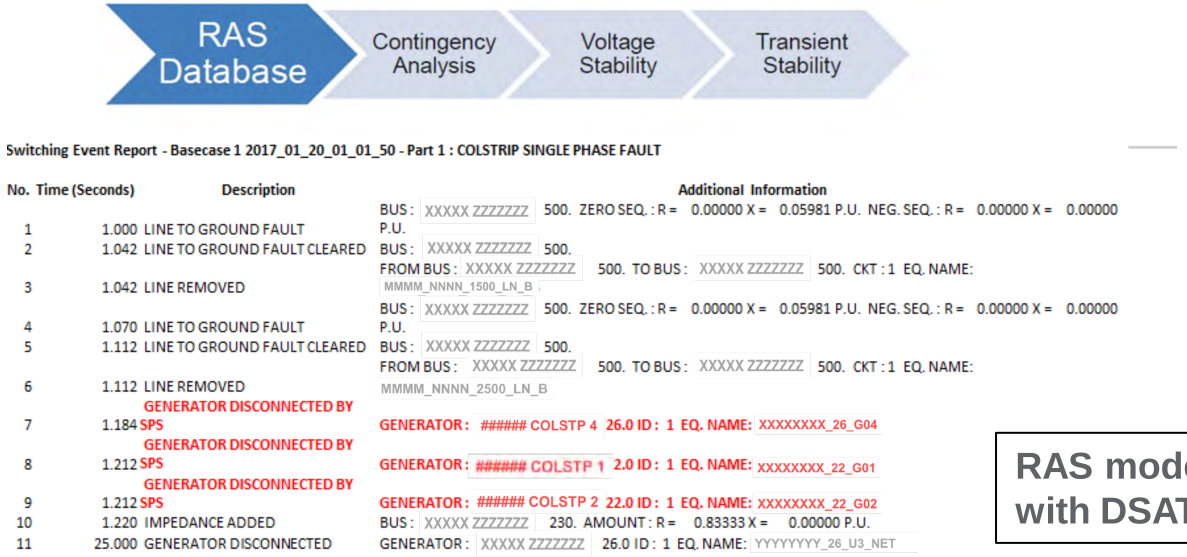
RAS interface in PSS/E power flow loop[*]

[*] Siemens, PSS/E Advanced Contingency Analysis and RAS Module document, available online: https://assets.new.siemens.com/siemens/assets/api/uuid:13592114fa75914812edf89f7ed6f8849b23d63e/psse-advcontingencyanalysisandras-module-flyer.pdf

Modeling RAS in Transient Stability Planning Study

- Time domain simulation usually will be performed to analyze the transient stability analysis in system planning; customized user defined model could be created and used in PSS/E to be executed within the time domain simulation.
- New software model/package in future software release
- For utility members in U.S. Western Interconnection, the RAS models in PSLF and DSATools can be activated in the time domain simulation.





Switching Event Report - Basecase 1 2017_01_20_01_01_50 - Part 1 : COLSTRIP SINGLE PHASE FAULT

No.	Time (Seconds)	Description	Additional Information
1	1.000	LINE TO GROUND FAULT	BUS : XXXXX ZZZZZZZ 500. ZERO SEQ. : R = 0.00000 X = 0.05981 P.U. NEG. SEQ. : R = 0.00000 X = 0.00000 P.U.
2	1.042	LINE TO GROUND FAULT CLEARED	BUS : XXXXX ZZZZZZZ 500.
3	1.042	LINE REMOVED	FROM BUS : XXXXX ZZZZZZZ 500. TO BUS : XXXXX ZZZZZZZ 500. CKT : 1 EQ. NAME: MMMM_NNNN_1500_LN_B
4	1.070	LINE TO GROUND FAULT	BUS : XXXXX ZZZZZZZ 500. ZERO SEQ. : R = 0.00000 X = 0.05981 P.U. NEG. SEQ. : R = 0.00000 X = 0.00000 P.U.
5	1.112	LINE TO GROUND FAULT CLEARED	BUS : XXXXX ZZZZZZZ 500.
6	1.112	LINE REMOVED	FROM BUS : XXXXX ZZZZZZZ 500. TO BUS : XXXXX ZZZZZZZ 500. CKT : 1 EQ. NAME: MMMM_NNNN_2500_LN_B
7	1.184	GENERATOR DISCONNECTED BY SPS	GENERATOR : ###### COLSTP 4 26.0 ID : 1 EQ. NAME: XXXXXXXX_26_G04
8	1.212	GENERATOR DISCONNECTED BY SPS	GENERATOR : ###### COLSTP 1 2.0 ID : 1 EQ. NAME: XXXXXXXX_22_G01
9	1.212	GENERATOR DISCONNECTED BY SPS	GENERATOR : ###### COLSTP 2 22.0 ID : 1 EQ. NAME: XXXXXXXX_22_G02
10	1.220	IMPEDANCE ADDED	BUS : XXXXX ZZZZZZZ 230. AMOUNT : R = 0.83333 X = 0.00000 P.U.
11	25.000	GENERATOR DISCONNECTED	GENERATOR : XXXXX ZZZZZZZ 26.0 ID : 1 EQ. NAME: YYYYYYYY_26_U3_NET

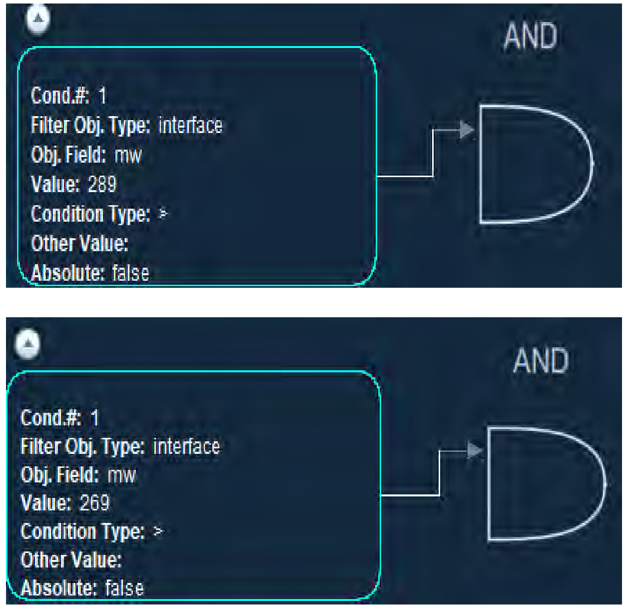
RAS model validation with DSATools [**]

[*] H. Zhang, S. Kincic and F. Howell, "Monitoring Bulk Electric System IROLs and RAS Operation by the Online Transient Stability Ananlysis Tool: Peak RC's Practice and Lessons Learned," 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2020, pp. 1-5.
[**] S. Kincic, H. Zhang and H. Yuan, "Implementation of Real-time Transient Stability for the Western Interconnection," *2019 IEEE Power & Energy Society General Meeting (PESGM)*, Atlanta, GA, USA, 2019, pp. 1-5.

Modeling Multiple RAS in System-level Planning Studies

- PNNL's Dynamic Contingency Analysis Tool (DCAT)
  - 2011 WECC Heavy Summer Operating Case
  - All dynamic models in WECC Master Dynamics File (MDF)
  - 7000+ Additional protective relays [*] [**], and RAS [*]
  - New Composite Load data created by PNNL's Load Model Data Tool (LMDT)
- A sequence of cascading failure simulated in DCAT
  - Protection model response (Protection relay, RAS)
  - Power flow condition at major observation points (transmission path, substation)
- Intermediate/Post-event power flow condition

S-Line RAS [*]



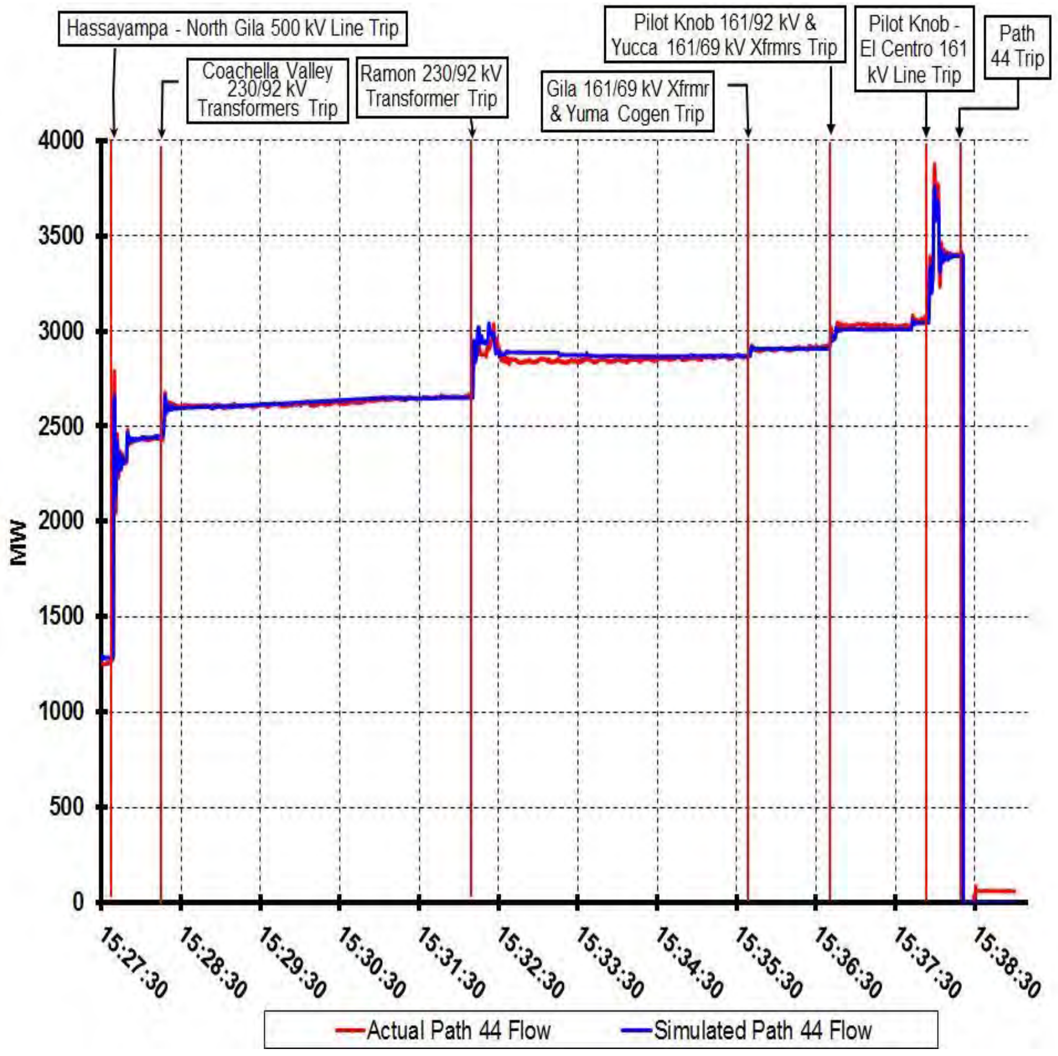
Protection Relay [*]

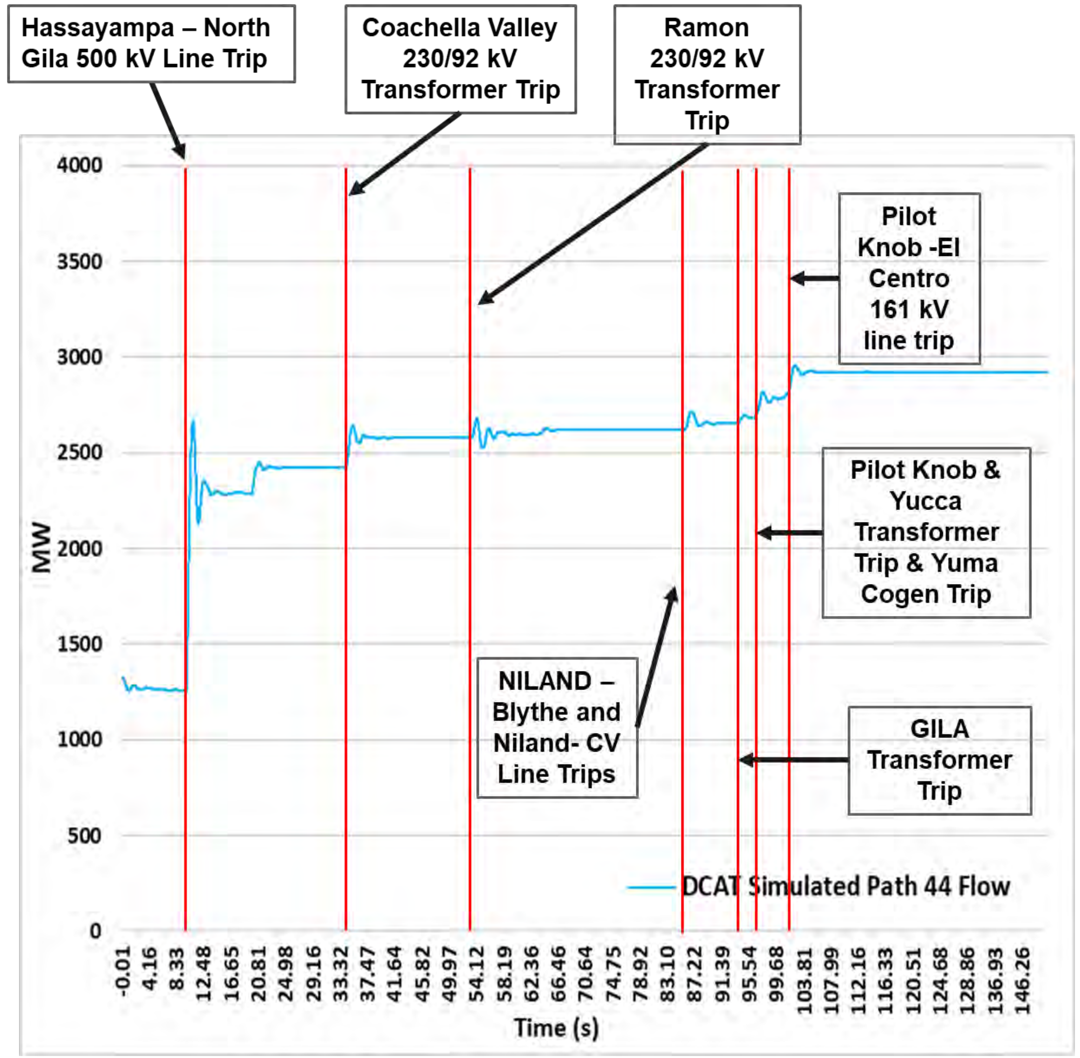
2011 Protection Relay at Coachella Substation	
Type:	Time Overcurrent Relay
Trip Setting	191 MVA, 127% of transformer normal rating

2011 Protection Relay at Area 21 IMPERIALCA, northern 92 kV	
Type:	Distribution under-voltage load shedding protection
Trip Setting	444 MW load tripped in IID

[*] "Arizona-Southern California outages on September 8, 2011", Prepared by the staffs of the FERC and the NERC, April 2012.
[**] X. Fan et al., "Bulk Electric System Protection Model Demonstration with 2011 Southwest Blackout in DCAT," 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2020, pp. 1-5.

Modeling Multiple RAS in System Blackout Event





DCAT evaluation of WECC Path 44 for 2011 Pacific Southwest Blackout, (a) Path flow plot provided in NERC Report [*], (b) Simulated path flow in PNNL DCAT analysis [**] (full protection actions sequence automation)

[*] "Arizona-Southern California outages on September 8, 2011", Prepared by the staffs of the FERC and the NERC, April 2012.
[**] X. Fan et al., "Bulk Electric System Protection Model Demonstration with 2011 Southwest Blackout in DCAT," 2020 IEEE Power & Energy Society General Meeting (PESGM), Montreal, QC, Canada, 2020, pp. 1-5.

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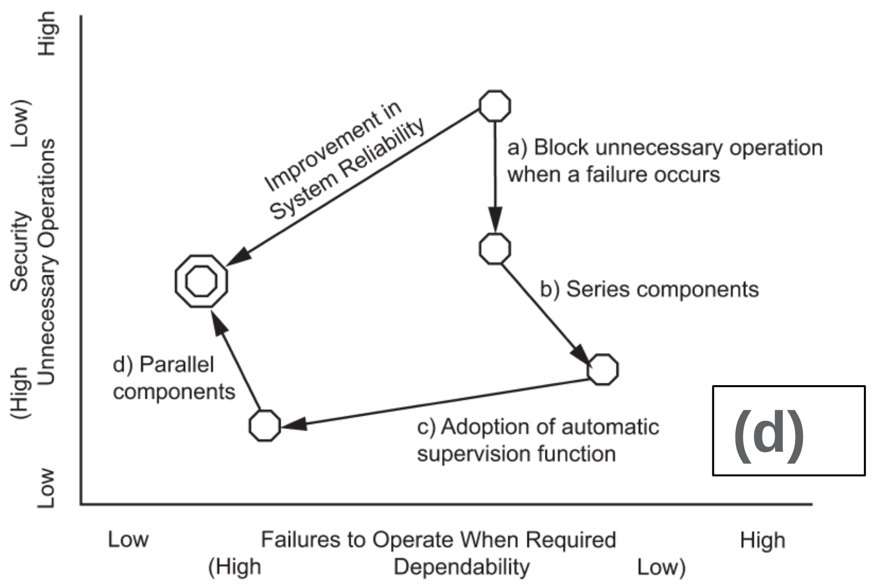
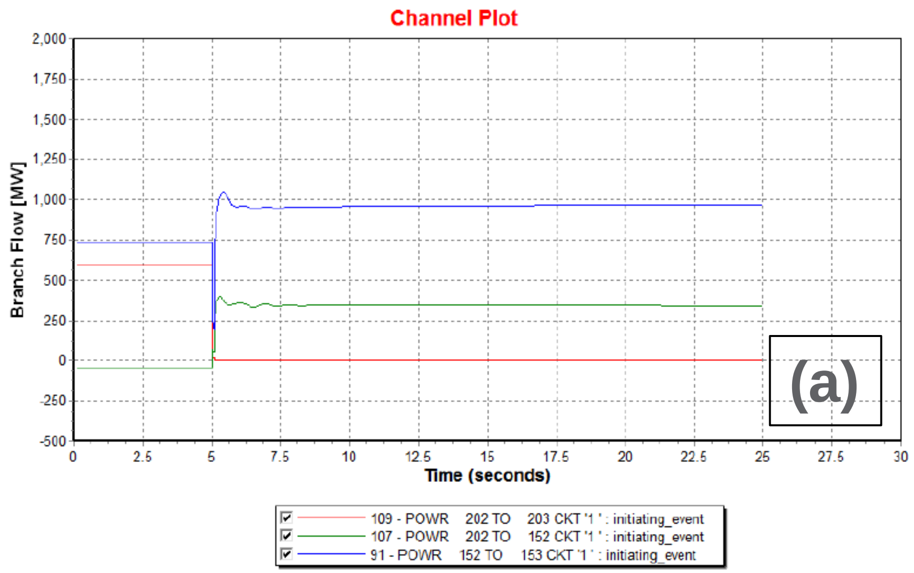
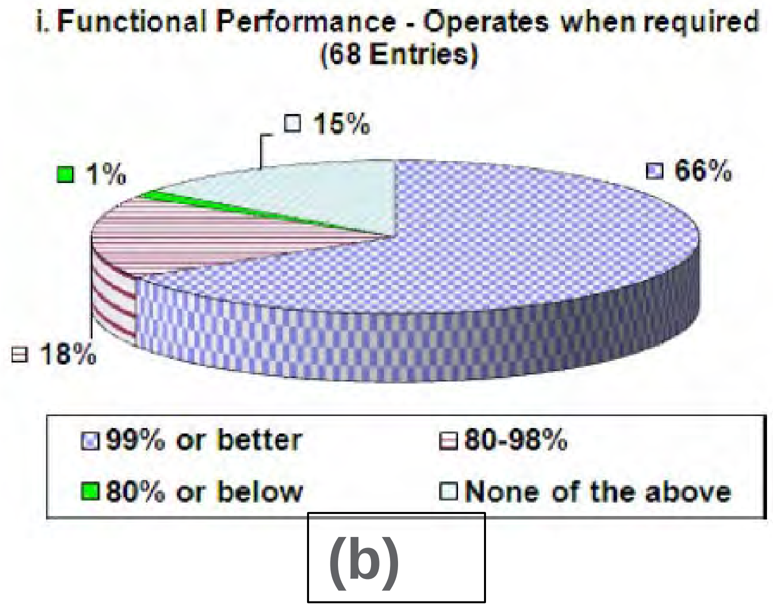
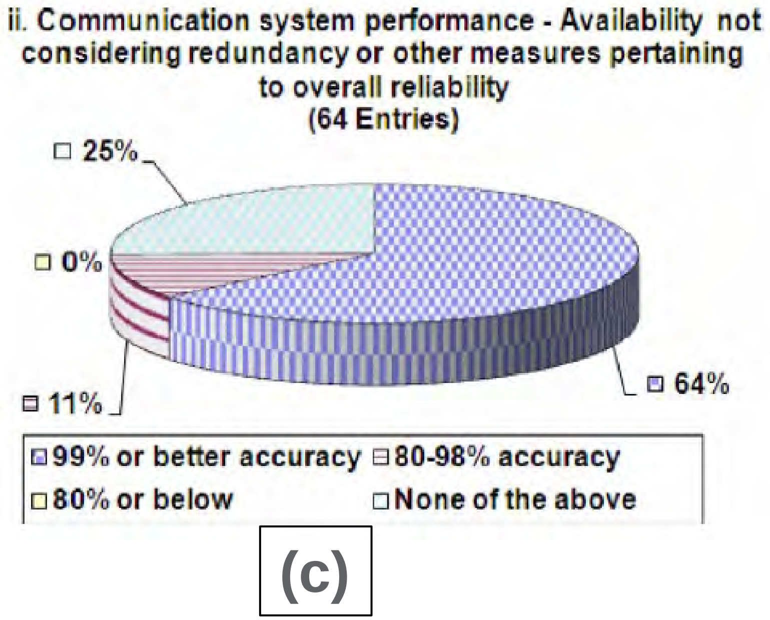
RAS Performance Evaluation

- RAS performance depends on a variety of technical and engineering design.
    a) Power system equipment control logic [*]
    b) Parallel controller implementation [**]
    c) Primary/alternative communication paths [**]
    d) other embedded design [***]









[*] Vyakaranam B., et al. 2019. Dynamic Contingency Analysis Tool 2.0 User Manual with Test System Examples. PNNL-29105. Richland, WA: Pacific Northwest National Laboratory.
[**] V. Madani et al., "IEEE PSRC Report on Global Industry Experiences With System Integrity Protection Schemes (SIPS)," in IEEE Trans.on Power Delivery, vol. 25, no. 4, pp. 2143-2155, Oct. 2010.
[***] "IEEE Guide for Engineering, Implementation, and Management of System Integrity Protection Schemes," in IEEE Std C37.250-2020 , pp.1-71, 17 June 2020, doi: 10.1109/IEEESTD.2020.9120373.

RAS Model Data Standards

- WECC defined a Common RAS Model format, all major grid software vendors have adopted or been implementing RAS functions based on this.
- WECC Common RAS Model Format
  - RemedialAction
  - RemedialActionElement
  - ModelFilter
  - ModelFilterCondition
  - ModelCondition
  - ModelCondition Details
  - ModelExpression

Example for WECC Common RAS Model Format [*]

```
RemedialAction(Name,     Skip,  Memo)
{
"Cowboy RAS"                  "NO" ""
"Viking RAS"                  "NO" ""
"Dolphin-Raider RAS"          "NO" ""
"Viking-Dolphin 1 Overload"   "NO" ""
"Viking-Dolphin 2 Overload"   "NO" ""
}
RemedialActionElement (RemedialAction, Object, Action, Criteria,
                       CriteriaStatus, TimeDelay, InclusionFilter, Comment)
{
"Cowboy RAS"    "GEN 31 1" "OPEN" "OPEN Cowboy G1"    "TOPOLOGYCHECK" 0 "" ""
"Viking RAS"    "INJECTIONGROUP 'Viking G1 and G2'" "OPEN" "OPEN Viking G1 and G2"
                                                  "TOPOLOGYCHECK" 0 "" ""
"Dolphin-Raider RAS" "GEN 28 1" "OPEN" "Dolphin-Raider 1 138 kV Line"
                                                  "TOPOLOGYCHECK" 0 "" ""
"Viking-Dolphin 1 Overload" "BRANCH 28 29 1" "OPEN" "Viking-Dolphin 1 345/138 Over 135%"
                                                  "POSTCHECK" 0 "" ""
"Viking-Dolphin 2 Overload" "BRANCH 28 29 2" "OPEN" "Viking-Dolphin 2 345/138 Over 135%"
                                                  "POSTCHECK" 0 "" ""
}
```

[*] J. Weber, PowerWorld Simulator Version 20 Manual, Auxiliary File Format Description for Specifying Contingency Definitions and Remedial Actions. Feb. 5, 2019.
Available online: https://www.powerworld.com/WebHelp/Content/Other_Documents/PowerWorld_RASFileFormat.pdf

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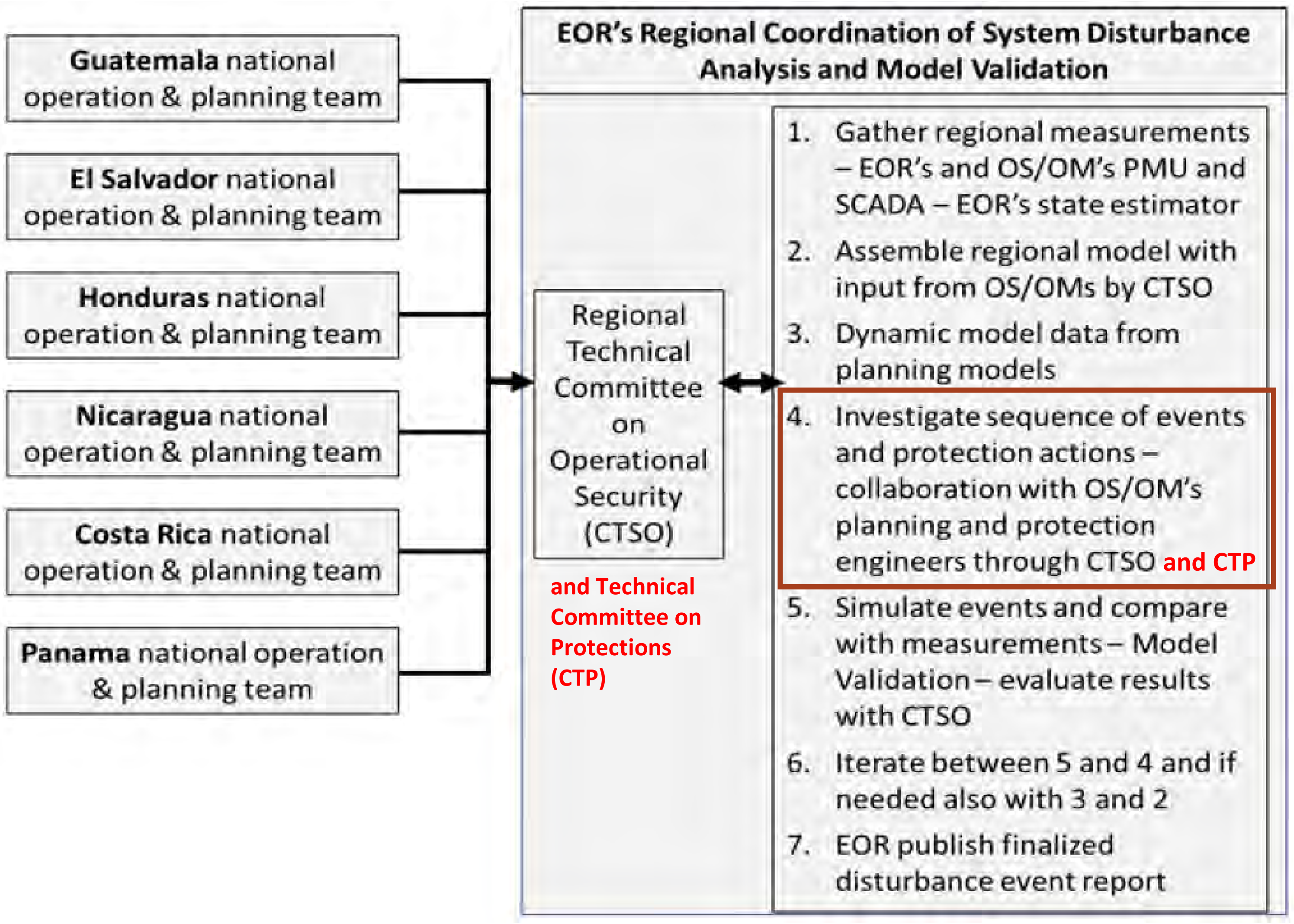
Ideas for Applications to Central America
(Coordination Examples)

Existing Collaboration in Central America and Mexico

- Regional technical working groups formed by EOR and 6 national OS/OMs collaborate on system disturbance analysis
  - Regional Technical Committees on Operational Security (CTSO) and on Protection (CTP) cover ECS
  - Analysis of ECS operation is part of the activities – if ECS maloperation is observed, preventive and corrective actions are adopted
  - Protection engineers collaborate with planning engineers
- EOR approves and can require new and modifications to ECS, as stated in RMER
- AMM, CENACE, and EOR also collaborate in technical topics related to Guatemala-Mexico interconnection



X. Fan et al., "Model Validation Study for Central American Regional Electrical Interconnected System," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2021

Implementation of ECS review, testing, and verification procedures

- OS/OMs and EOR should consider adding more ECS review, testing, and verification procedures at the regional level and in collaboration with CENACE
- Regional technical working groups (CTSO and CTP) in Central America that currently analyze events and study ECS operation could be part of a regional ECS review committee, in charge of formally reviewing ECS and recommending approval
- Regional technical rules in Reglamento del Mercado Eléctrico Regional (RMER) may need to be amended – EOR regulatory affairs office can collaborate with CTSO and CTP
- AMM, CENACE, and EOR may collaborate for establishing review, testing, and verification on ECS that affect both Central America and Mexico – such as the EDALTIBV ECS in Guatemala-Mexico interconnection

Incorporating ECS models in PSS/E and in EMS models for real time contingency analysis

- ECS models in PSS/E
  - Adopt standard formats across all OS/OMs and EOR for ECS models
    - ✓ PowerWorld, PSS/E, PSLF have implemented standardized formats
  - EOR and OS/OMs can collaborate on incorporating ECS models for the Central American regional system (SER)
    - ✓ Regional technical working groups can be leveraged
    - ✓ The existing experience in AMM (Guatemala) and CND-ETESA (Panama) can be very useful

- ECS models in Energy Management System (EMS) in control centers
  - Results from real-time contingency analysis applications in EMS can be affected significantly by ECS
  - ECS models should also be incorporated into EMS tools

Implementing ECS monitoring in control centers

- AMM monitors interarea oscillations that activate an ECS at Guatemala-Mexico interconnection [*]
- EOR, AMM, and CENACE may collaborate to determine other ECS that need monitoring at national or regional control centers
- Besides monitoring, system operators in North America also implement RAS arming functions based on real-time system conditions, such as in BC Hydro [**], and the Reliability Coordinators collect real-time arming information

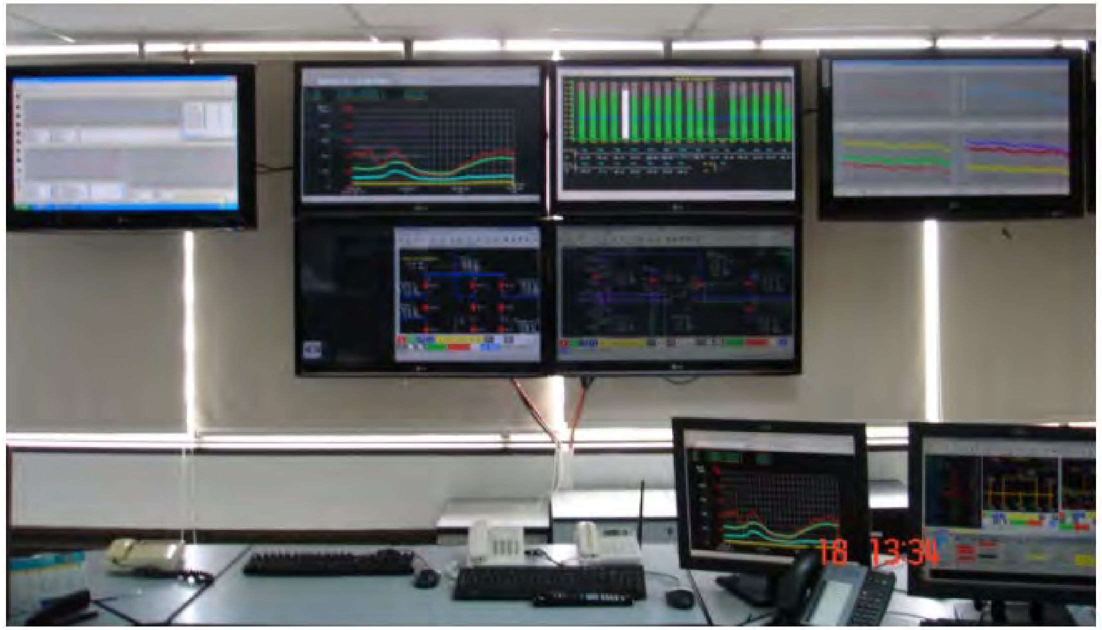


Fig. 5. Synchrophasor data complement traditional SCADA

Figure from: [*] J.V. Espinoza, A. Guzman, F. Calero, M. Mynam, and E. Palma, “Wide-Area Measurement and Control Scheme Maintains Central America’s Power System Stability” Wide-Area Protection and Control Systems, 2017

[**] Yao, Ziwen, et al. "Forewarned is forearmed: An automated system for remedial action schemes." *IEEE Power and Energy Magazine* 12.3 (2014): 77-86.

Coordination between Mexico, Guatemala, and EOR to model Mexico-Guatemala ECS

- Coordination of modeling practices to predict ECS action for planning and operation studies
  - Updating and maintaining Mexico’s equivalent representation for Central America
  - Creating, updating, and maintaining Central America’s equivalent representation for Mexico
  - Incorporating ECS model into PSS/E and real-time models at CENACE, AMM, and EOR

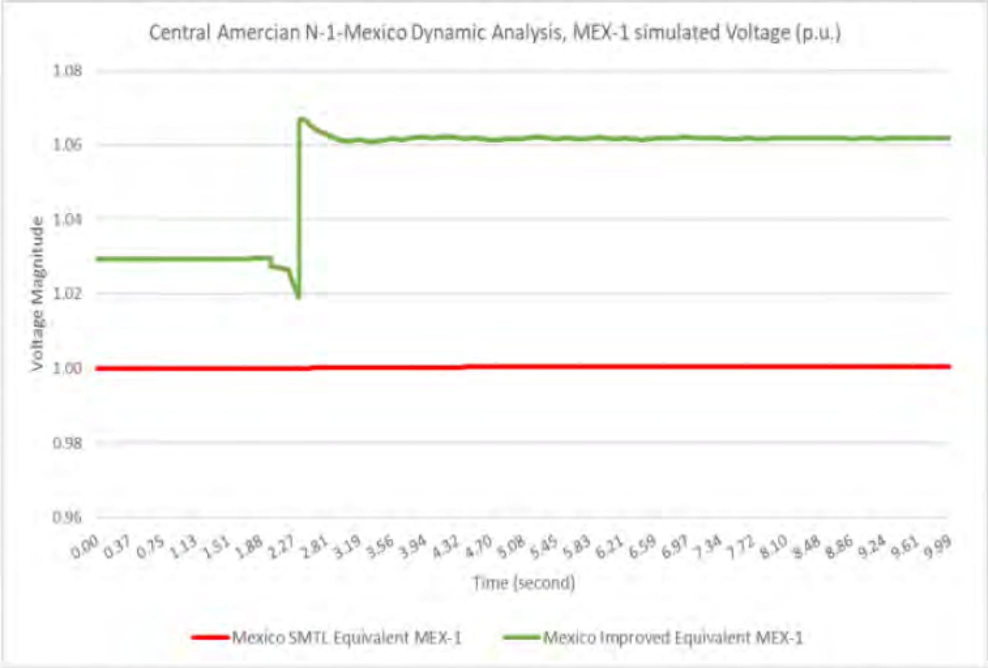


Figure 4. Voltage comparison of bus MEX-1 for different Mexico equivalent models.

X. Fan et al., "Model Validation Study for Central American Regional Electrical Interconnected System," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2021

Upcoming Webinars

Resilience and Extreme Event Planning – May 12th and 19th, 2021

Transfer Capability and Coordinated Stability Studies – June 9th and 16th, 2021

Renewable Integration – July 14th, 2021

Final Session – August 18th, 2021

Thank you!

Questions?

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