Dynamic Contingency Analysis Tool (DCAT) – A Framework for Analysis of Extreme Events in Power Systems

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Challenges Facing the Power Industry in Performing Cascading Outage Analysis

- Results of a recent IEEE Cascading Failure Working Group survey on the Analysis of Cascading Outages show the challenges facing the power industry:
  - 70% of the responders indicated that cascading outage analysis in their organization is not an automated process.
  - 50% of the responders were not satisfied with currently available tools for analysis of cascading outages.
  - Dynamic simulation of cascading outages, which should include protection system modeling, was cited as the most critical feature that present tools fail to address.

How Can DCAT Bridge These Gaps?

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- DCAT attempts to bridge multiple gaps in cascading-outage analysis in a single, unique prototype tool capable of automatically simulating and analyzing cascading sequences in real systems using multiprocessor computers.
  - It uses a hybrid dynamic and steady-state approach to simulating the cascading outage sequences that includes both fast dynamic and slower steady-state events.
  - It integrates dynamic models with protection scheme models for generation, transmission, and load.
  - It models special protection systems (SPS)/remedial action schemes (RAS) and automatic and manual corrective actions.
- The current prototype DCAT implementation has been developed as a Python code that accesses the simulation functions of the Siemens PSS®E planning tool (PSS/E).

Overall DCAT Project Phase I Framework

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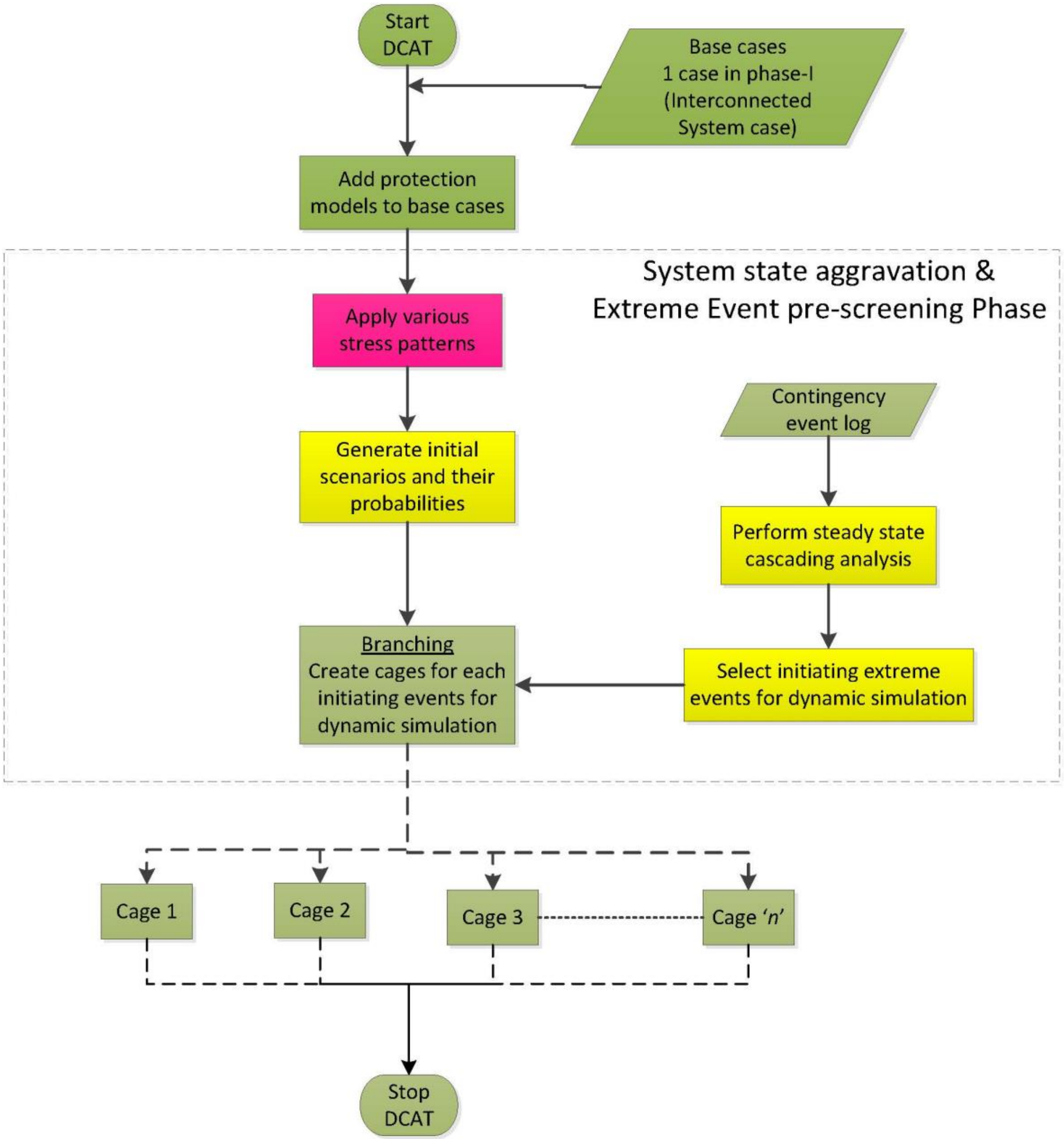
Framework

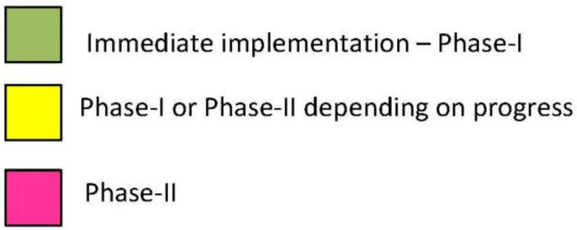
- Survey existing approaches, industry practice, tools, and gaps in performing cascading outage analysis. (Sec. 1)
- Develop a hybrid dynamic and steady-state approach to mimic the cascading failure process that includes both fast dynamic and slower events. (Sec. 2)
- Integrate dynamic models with protection scheme models. Use NERC standards for relay settings. (Sec. 3)
- Perform post-dynamic analysis that models SPS/RAS, automatic and manual corrective actions. (Sec. 4)
- Run simulations for the test and full interconnection system models to demonstrate key concepts of the DCAT project. (Sec. 5)
- Perform steady-state cascading outage analysis using TransCARE for filtering initiating events and implementing and testing the concept of critical events corridors. (Sec. 6)
- Share lessons learned and suggest a roadmap for further improvements. Provide technology outreach and dissemination. (Sec. 7)

Industry Partnership

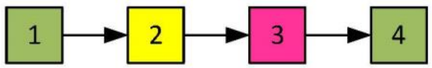
- Siemens PTI
  - PSS/E is used for dynamic/steady-state analysis of cascading events.
  - Multiple copies of PSS/E were provided to develop high performance computing capability for cascading events.
  - Provided help with protection modeling.
  - Provided consulting support for using advanced features in PSS/E.
- EPRI
  - TransCARE is used for steady-state-based cascading outage analysis for prescreening of initiating events.
- ERCOT
  - Played advisory role through biweekly web conferences to discuss issues and progress.
- DCAT creates an open architecture for extreme events analysis. Any software vendor meeting technical requirements can connect.

DCAT Computational Flow Chart (part A)





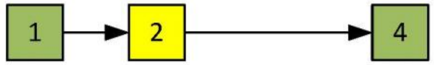
Note: Flow chart shows progressive implementation of DCAT methodology. Incomplete parts of the methodology do not break the flow chart, but rather can be considered to allow the flow chart without blocking it. For example,



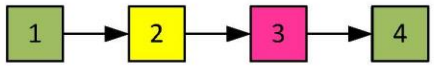
can be shown in different phases as depicted here

Immediate implementation – Phase-I

Phase-I or Phase-II depending on progress



Phase-II



DCAT Computational Flow Chart (part B)

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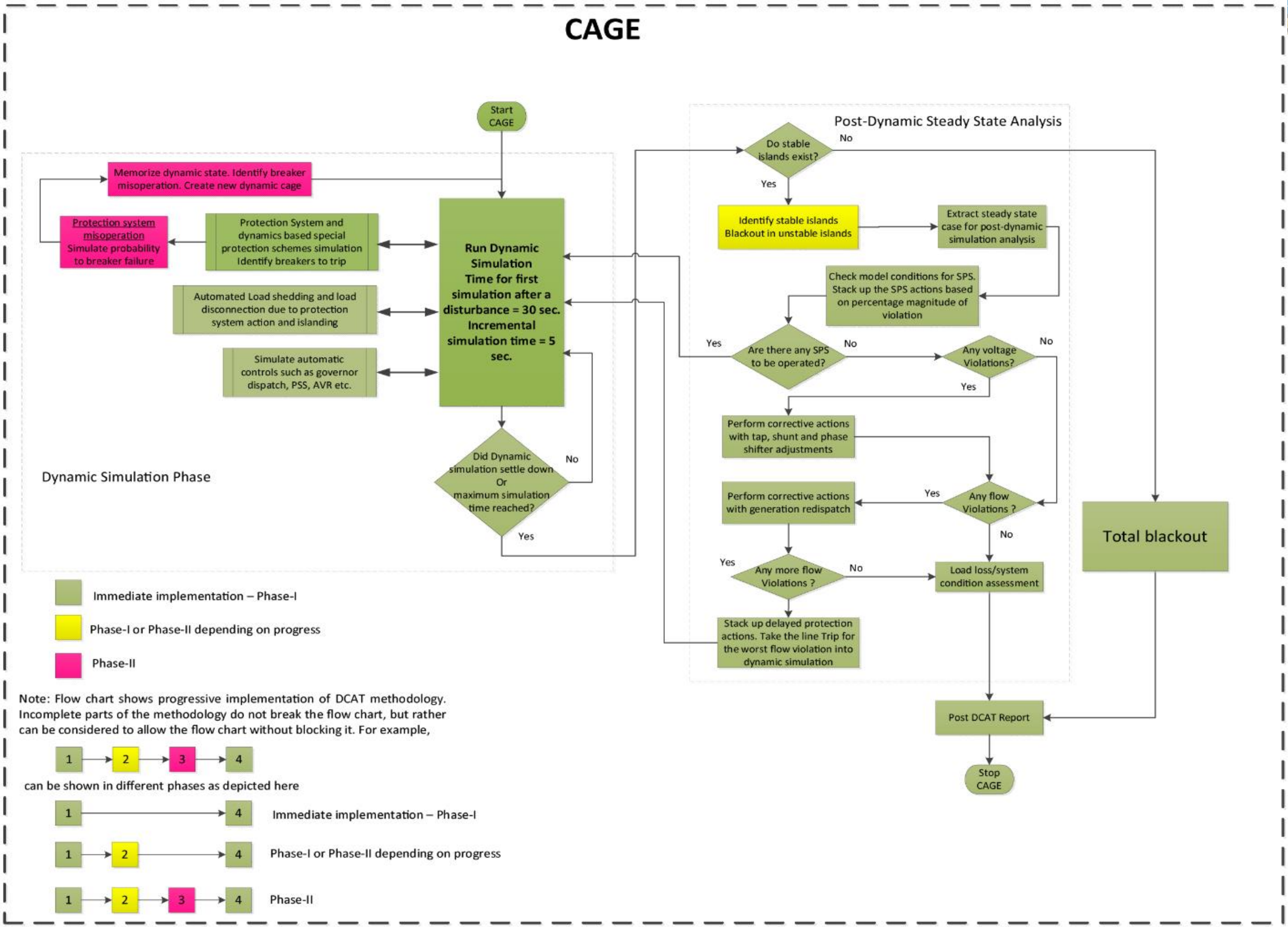
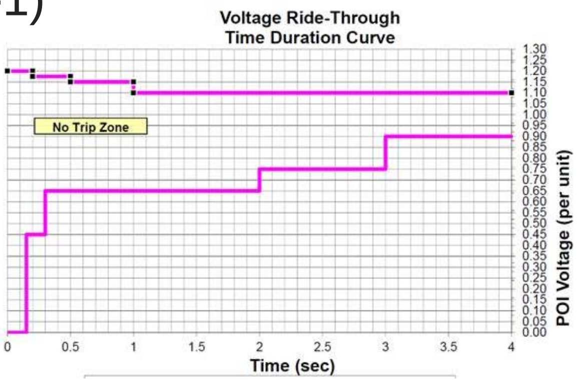
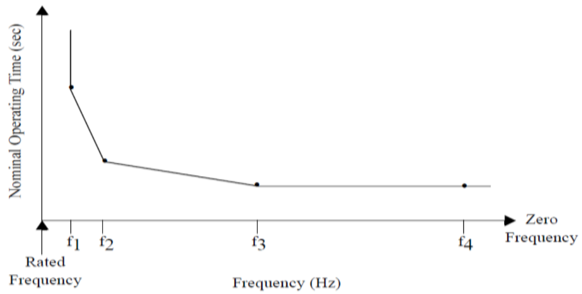


Protection Modeling in Phase I

- Need to model protection action in order to simulate cascading events
- Used a subset of the protection device models in PSS/E
  - Generator bus protection (NERC Standard PRC-024-1)
    - Under-voltage and over-voltage
    - Under-frequency and over-frequency
    - Out of step (user-defined model that excludes nonsynchronous machines)
  - Load shedding
    - Under-frequency (frequency responsive non-firm load)
    - Under-frequency and under-voltage firm load shedding
  - Transmission protection
    - Distance relay protection (dynamic simulation)
    - Overcurrent protection (steady-state simulation)
    - Breaker location for placement of protection within the transmission network and the associated operation of zones of protection

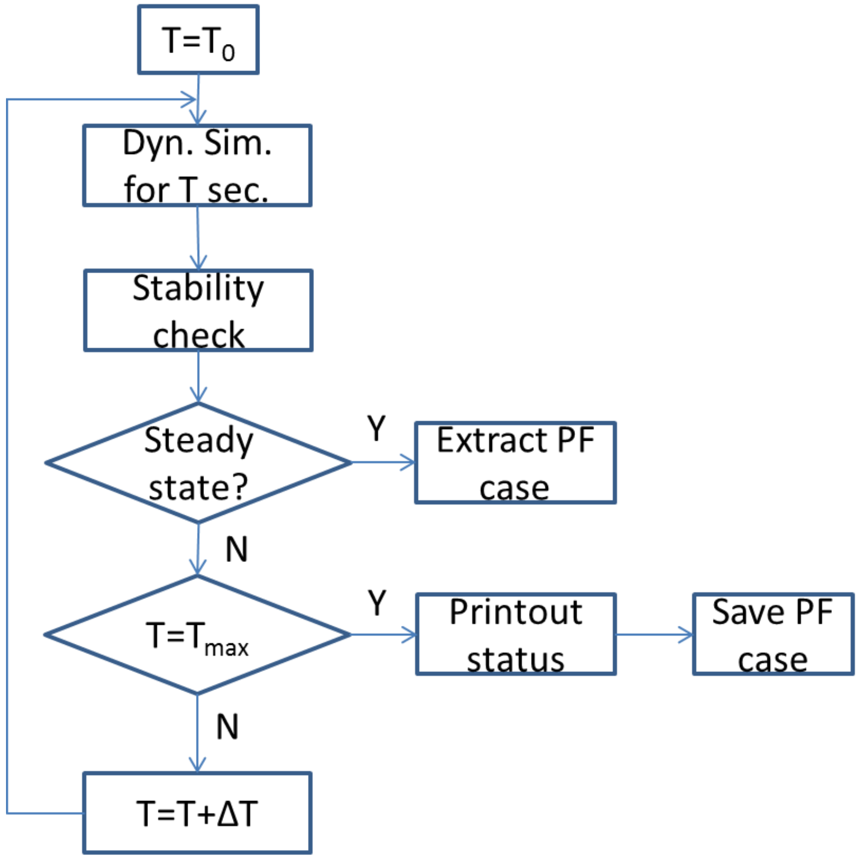




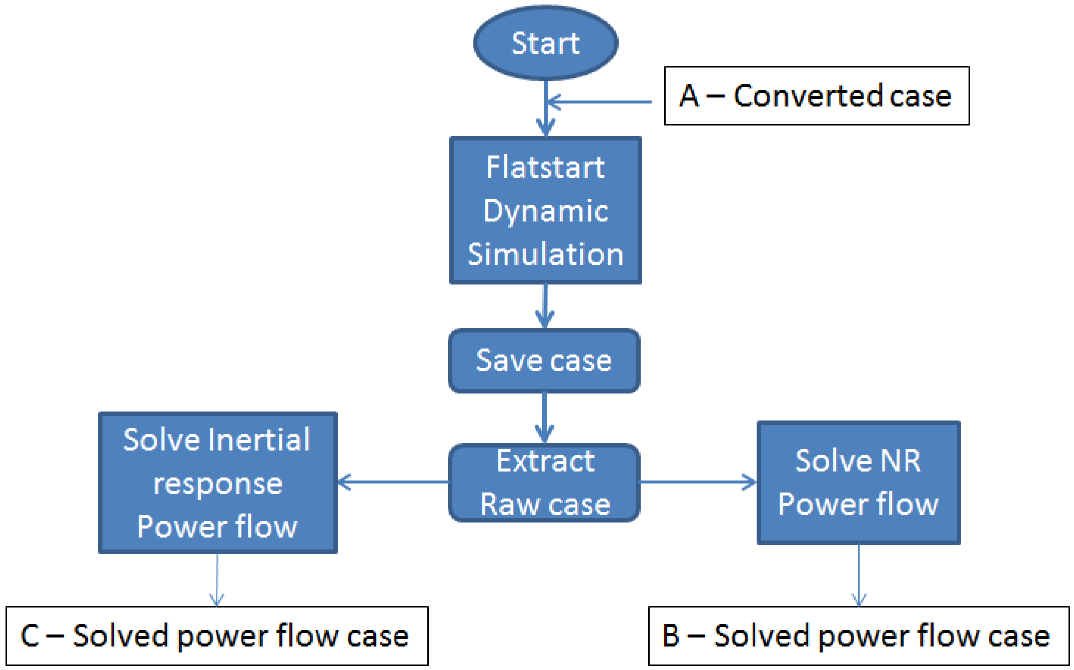
- Modeling of RAS/SPS in the steady-state post-dynamic analysis

Verification if System Reaches a Stable Point at the end of Dynamic Simulation

- Dynamic simulation is a computationally intensive task. An appropriate trade-off is necessary to run the dynamic simulation long enough to capture the dynamic response of the system.
- The appropriate time can be determined by having stability checks at intermediary times that could stop the dynamic simulation.
- The simulation can initially run for 30 seconds. After 30 seconds, every 5 seconds, values of standard deviation of the speeds of all generators are compared with a certain tolerance.



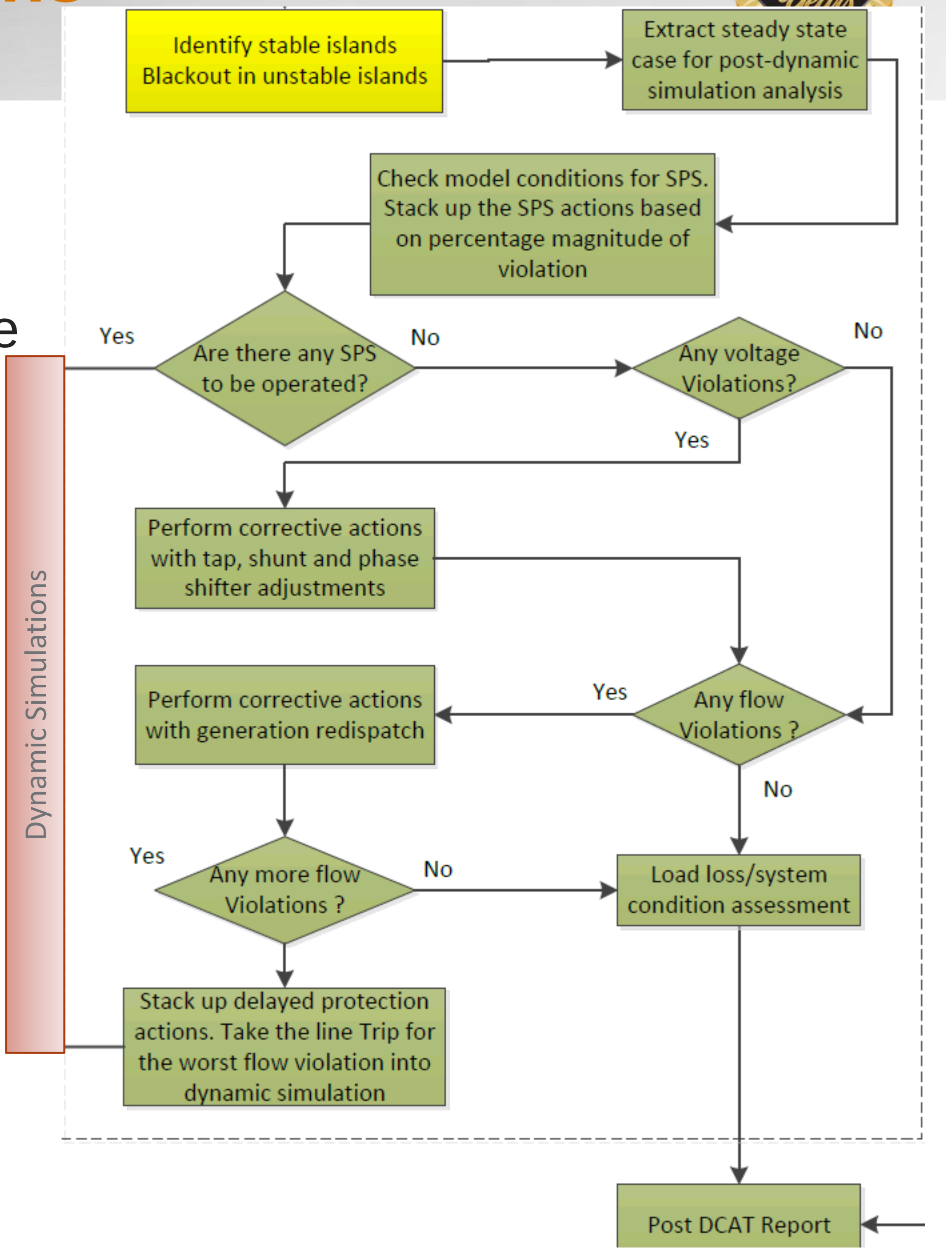
DCAT Post-Dynamic Simulation Analysis – Extracting a Steady-State Case



		Pre-Dynamic		Post-Dynamic Newton-Raphson Power Flow				Post-Dynamic INLF (Inertial Response)			
Bus #	Bus Name	Bus Voltage		Bus Voltage		Absolute Difference		Bus Voltage		Absolute Difference	
		Mag (pu)	Angle (deg)	Mag (pu)	Angle (deg)	Δmag	Δangle	Mag (pu)	Angle (deg)	Δmag	Δangle
3018	CATDOG_G	1.0218	-4.08	1.0218	-4.08	0	0	1.0217	-4.08	1E-04	0

DCAT Post-Dynamic Simulation Analysis – Corrective Actions

- Extreme events could result in a significant power mismatch between generation and load. Consequently, a power flow solution might not converge without appropriate setup.
- As part of DCAT methodology, after performing a dynamic simulation, corrective actions could be taken by the operator to make sure that voltage and flow violations are reduced.
- These actions are
  - SPS/RAS
  - automatic actions for voltage violation corrections
  - generation redispatch and load shedding to avoid the tripping of overloaded lines.



Emergency control of power systems

- Power systems operates with defined system conditions
  - Line ratings
  - Voltage limits
  - Generator real and reactive power dispatch
  - Generator ramp limits
- System is considered to operate in "Emergency condition" if some of the operational limits are violated
- Corrective control actions can be performed to bring the system out of "Emergency condition"
- Control actions
  - Preventive
  - Corrective

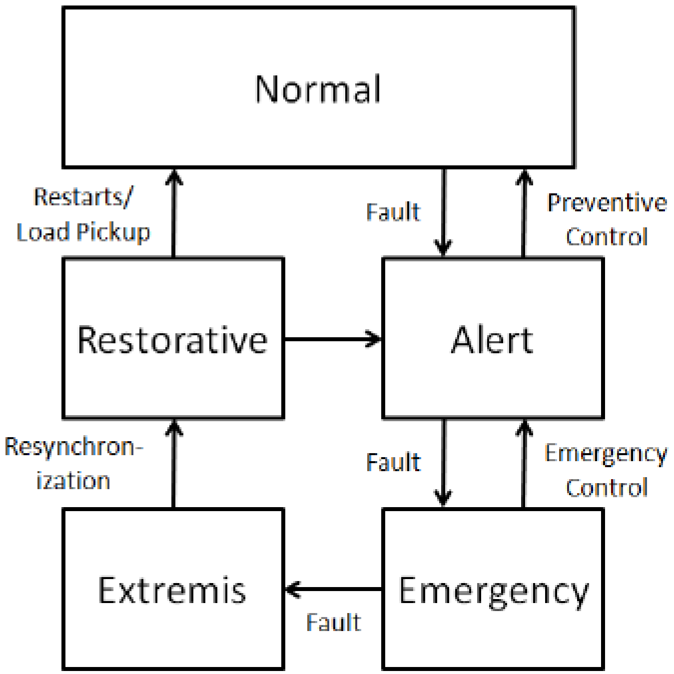


Fig.1: Power systems operational states

Emergency control of power systems: Mathematical formulation

- Emergency control actions can be formulated as optimization problem
- Minimize corrective actions to mitigate emergency conditions

$$\min \sum_{r=1\ldots Na} C_r \cdot \Delta A_r^2$$

- Where Ci is the weight coefficient, and ΔA_r set of available actions:
  - MW Dispatch – fixed gen voltage setpoints
  - MVar Dispatch – Voltage setpoints change
  - Capacitor and Reactor Switching
  - Transformer Tap Change
  - Phase Shifter settings
  - Line Switching (In and Out), including Switching Not Affected Lines
  - Load Curtailment

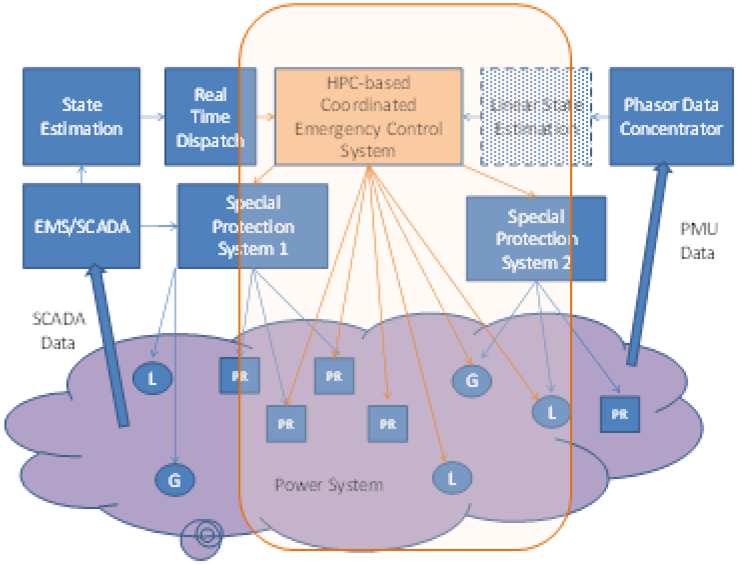


Fig. 2- A conceptual view of the Coordinated Emergency Control and Protection System

Emergency control of power systems: Mathematical formulation

- Emergency control actions can be formulated as optimization problem
- Minimize corrective actions to mitigate emergency conditions

$$\min \sum_{r=1\ldots Na} C_r \cdot \Delta A_r^2$$

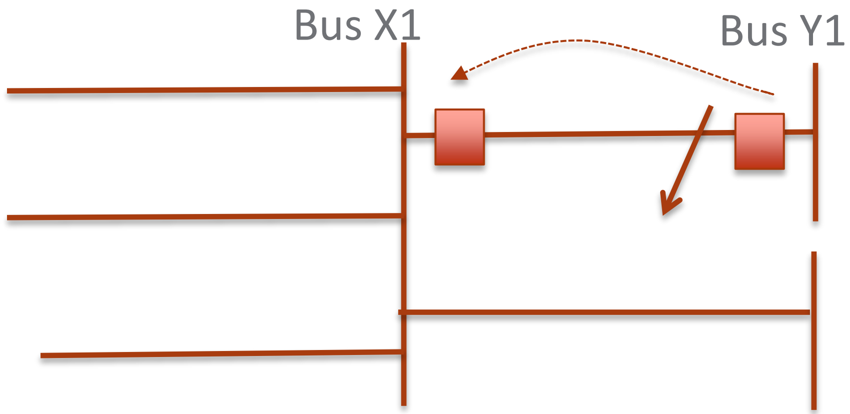
- Subjected to:
  - Power balance equations
  - Line flow limits
  - Bus voltage limits
  - Generator real and reactive power limits
- Additional constraints:
  - Constraint that describes maximum allowable number of corrective actions

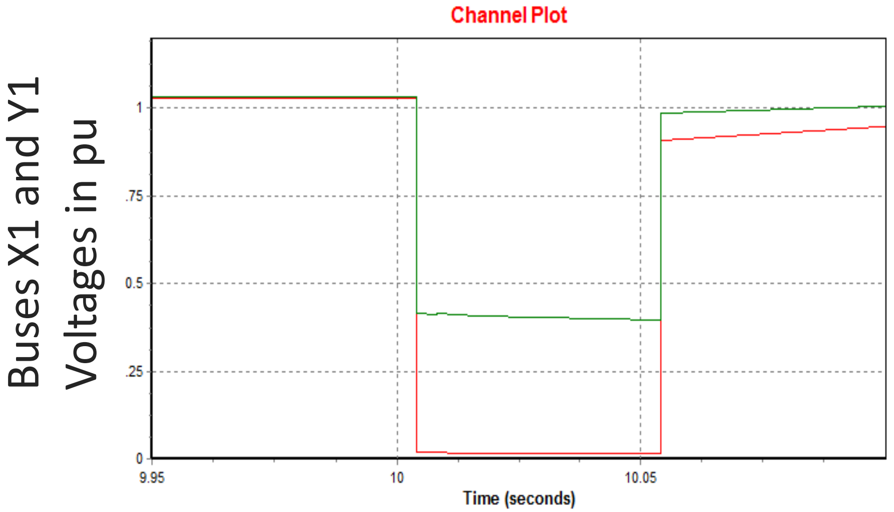
$$Na \le Na\,\mathrm{max}$$

  - Constraint for linearized operational boundaries

$$\sum_{j=1}^{Nb} \alpha_{ij} P_j + \beta_{ij} Q_j \le \Pi_i, \ \text{for all i}$$

Example 1 – Line Fault with a Pilot Scheme (Transfer Trip Enabled)





- A line fault is applied on one of the lines connected to Bus X1 at a distance of 90% from the bus. Distance relays are enabled on both ends of the line with an ability to send a transfer trip to the other end upon sensing a Zone 1 fault.
- Though the other end of the line (at Bus X1) sees a Zone 2 fault, this pilot scheme trips the breaker as soon as the other relay times out on the Zone 1 fault.
- Upon successful operation of both breakers, the fault is isolated and no other tripping actions occur.

Example 2 – Line Fault with No Pilot Scheme

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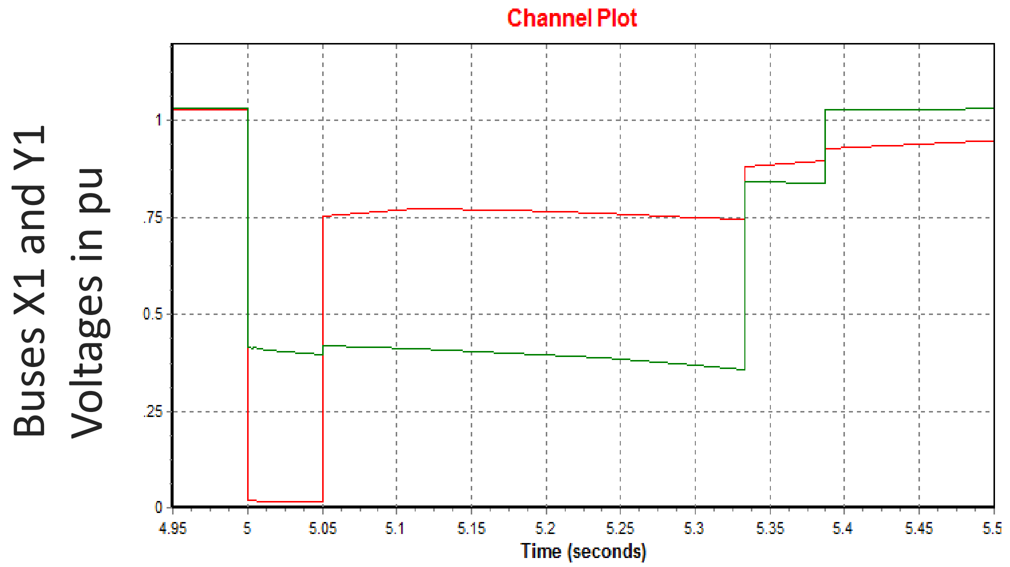

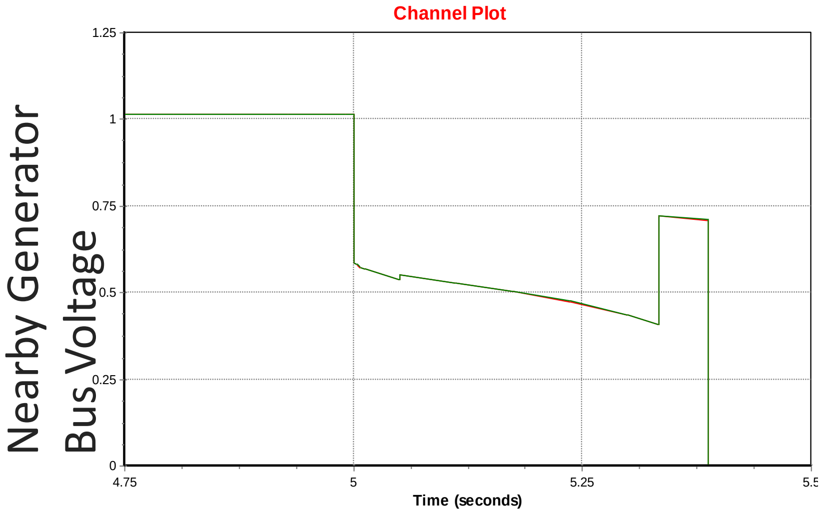

Gen. under voltage tripping

- Same as Example 1, but the communication channel for transfer trip failed.
- As a result of that, the near end of the line to the fault at Bus Y1 trips on the Zone 1 setting (4 cycles) and the other end of the line trips at the Zone 2 setting (22 cycles).
- Since the Zone 2 trip persists longer than the Zone 1 trip, many other relays would have their timers started and some would have cascaded trips.

Example 2 – Line Fault with No Pilot Scheme (2)

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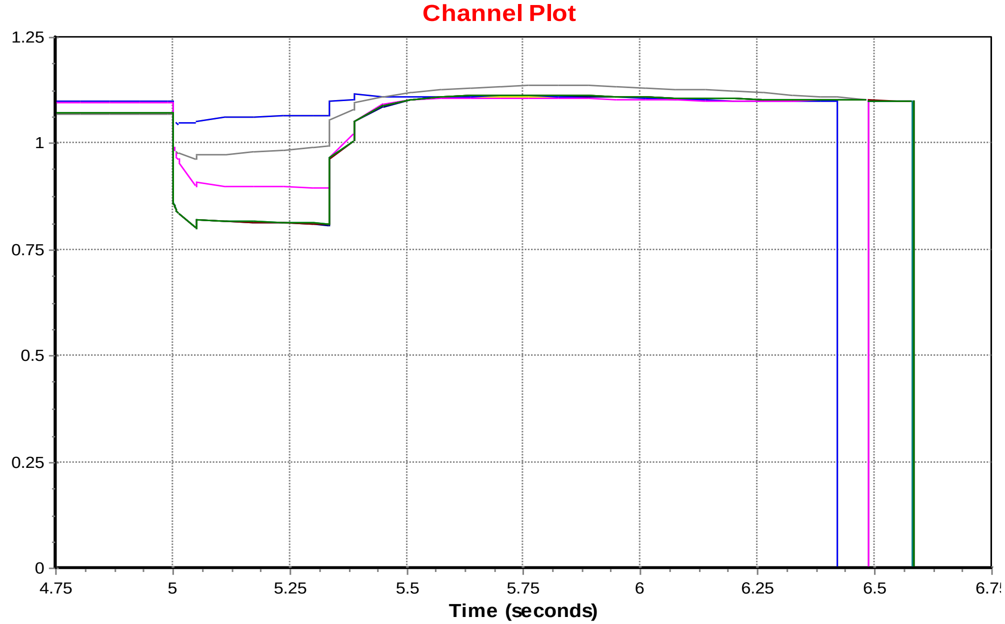
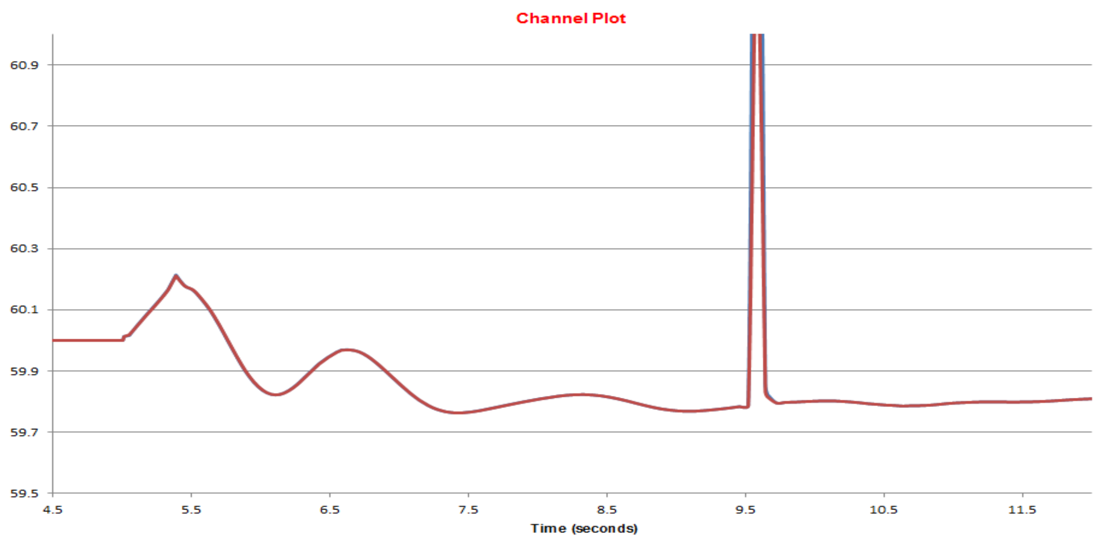
Generator Over-Voltage Trippings for Example 2



Generator Under-Frequency Tripping for Example 2



Example 2 – Results Summary

DISTR1	TimeOut	Busfrom	Busto	Ckt	
DISTR1	5.05	X1	X2	1	
DISTR1	5.333	Y1	Y2	1	
VTGTPA	TimeOut	Pgen	Qgen		
VTGTPA	5.387	1205	157		
VTGTPA	5.387	1195	153		
VTGTPA	6.421	68	28.8		
VTGTPA	6.421	67	28.8		
VTGTPA	6.487	17	14.8		
VTGTPA	6.487	17	14.8		
VTGTPA	6.571	15	0		
VTGTPA	6.579	69	6.59		
VTGTPA	6.583	71	6.59		
VTGTPA	6.583	70	6.78		
VTGTPA	6.583	68	6.59		
FRQTPA	TimeOut	Pgen	Qgen		
FRQTPA	9.662	7.53	7.37		
FRQTPA	9.662	5.42	0		
OutOfStep_new	TimeOut	Pgen	Qgen	AngleThr	AngleDev
OutOfStep_new	10.1374	0	-12.25	180	180.2261
VTGTPA	16.046	74.67	38		
VTGTPA	16.046	71.61	38		

Generation Loss (MW)	3,004
Load Loss (MW)	0
# of Total Tripping Actions	18
# of Special Protection Systems Triggered	0
# of Overloaded Lines	0
Corrective Actions	None

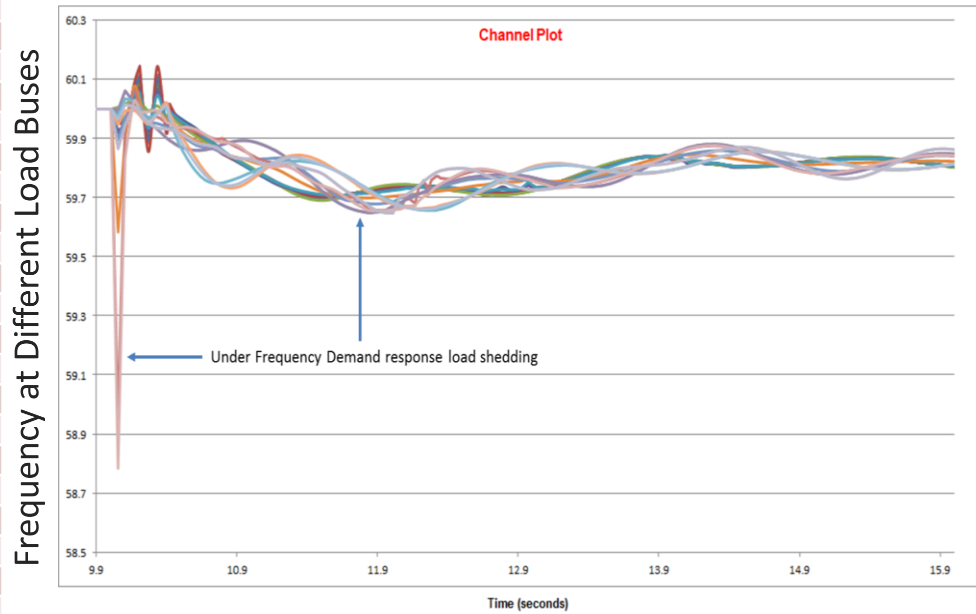
Example 3 – Demonstration of Under-Frequency Load Shedding after an Extreme Event

- A bus fault that lasted for six-cycles was introduced at a large substation.
- All elements connected to this substation were then tripped to isolate the fault.
- This was one of the extreme events that had the potential for many demand-response–based under-frequency load relays to act and shed a part of the load dynamically.
- A significant amount of generation was lost due to this fault, which was followed by many under-frequency load sheddings.
- At the end, the system was able to reach a stable point.

Generation Loss (MW)	**3,900**
Load Loss (MW)	**1,067**
# of Total Tripping Actions	**84**
# of Special Protection Systems Triggered	**0**
# of Overloaded Lines	**0**
Corrective Actions	**None**

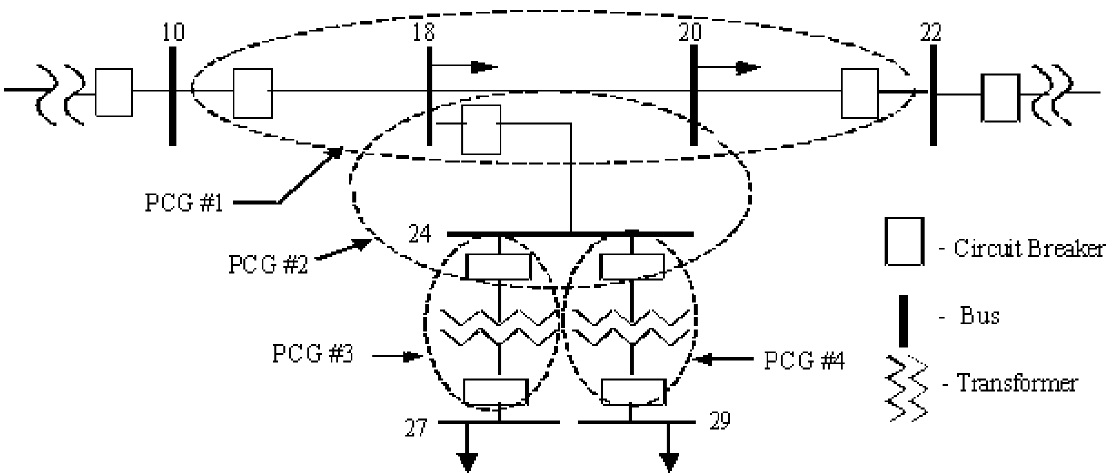
Example 3 – Demonstration of Under-Frequency Load Shedding after an Extreme Event

DISTR1	TimeOut	From	To				
DISTR1	10.054	X1	Y1				
DISTR1	10.054	X2	Y2				
FRQTPA	TimeOut	Pgen	Qgen				
FRQTPA	10.104	70.56	-10.05				
FRQTPA	10.104	70.56	-10.05				
OutOfStep_new	TimeOut	Pgen	Qgen	AngleThr	AngleDev		
OutOfStep_new	10.4207	1375	160.03	180	182.5495		
OutOfStep_new	10.4207	1375	180.03	180	181.8143		
LDSH_LDFR	TimeOut	Stage	Pshed	Qshed	ShedLp.u.InitL	Voltage	Frequency
LDSH_LDFR	11.529	1	13.68	5.97	0.3876	0.97	59.72
LDSH_LDFR	11.633	1	7.92	2.29	0.1646	1.01	59.7
LDSH_LDFR	11.675	1	5.74	2.15	0.6512	0.98	59.71
LDSH_LDFR	11.675	1	2.85	0.91	0.0905	1.03	59.71
LDSH_LDFR	11.687	1	1.99	0.45	0.1585	1.03	59.71
LDSH_LDFR	11.692	1	1.99	0.45	0.1654	0.97	59.71
LDSH_LDFR	11.7	1	1.5	0.35	0.1307	1.03	59.71
LDSH_LDFR	11.721	1	2.13	0.61	0.0392	1.03	59.71
LDSH_LDFR	11.733	1	5.39	1.12	0.2122	1	59.71
VTGTPA	TimeOut	Pgen	Qgen				
VTGTPA	11.737	50	30				
LDSH_LDFR	11.754	1	3.28	0.79	0.4316	0.99	59.71
LDSH_LDFR	11.762	1	4.58	1.01	0.237	1.01	59.72
LDSH_LDFR	11.767	2	7.1	2.04	0.1304	1.03	59.72
LDSH_LDFR	11.846	1	23.63	0.07	0.6513	1.01	59.65
LDSH_LDFR	11.896	1	14.24	4.68	0.6513	0.99	59.68
LDSH_LDFR	11.95	1	92.48	37.97	0.6513	1.02	59.66
LDSH_LDFR	12.008	1	0.51	0.1	0.0158	0.98	59.66
LDSH_LDFR	12.008	1	0	0	0.3372	1.02	59.65
LDSH_LDFR	12.008	1	19.51	5.69	0.3372	1.02	59.65
LDSH_LDFR	12.008	1	58.65	17.11	0.3372	1.02	59.65
LDSH_LDFR	12.008	1	78.16	22.8	0.3372	1.02	59.65
LDSH_LDFR	12.058	1	16.67	3.34	0.3799	1.02	59.67
LDSH_LDFR	12.062	2	11.91	2.39	0.2714	1.03	59.67
LDSH_LDFR	12.079	1	23.44	2.57	0.4162	1.02	59.67
LDSH_LDFR	12.083	1	1.31	0.18	0.1267	0.97	59.68
LDSH_LDFR	12.083	1	0.91	0.13	0.1267	0.97	59.68

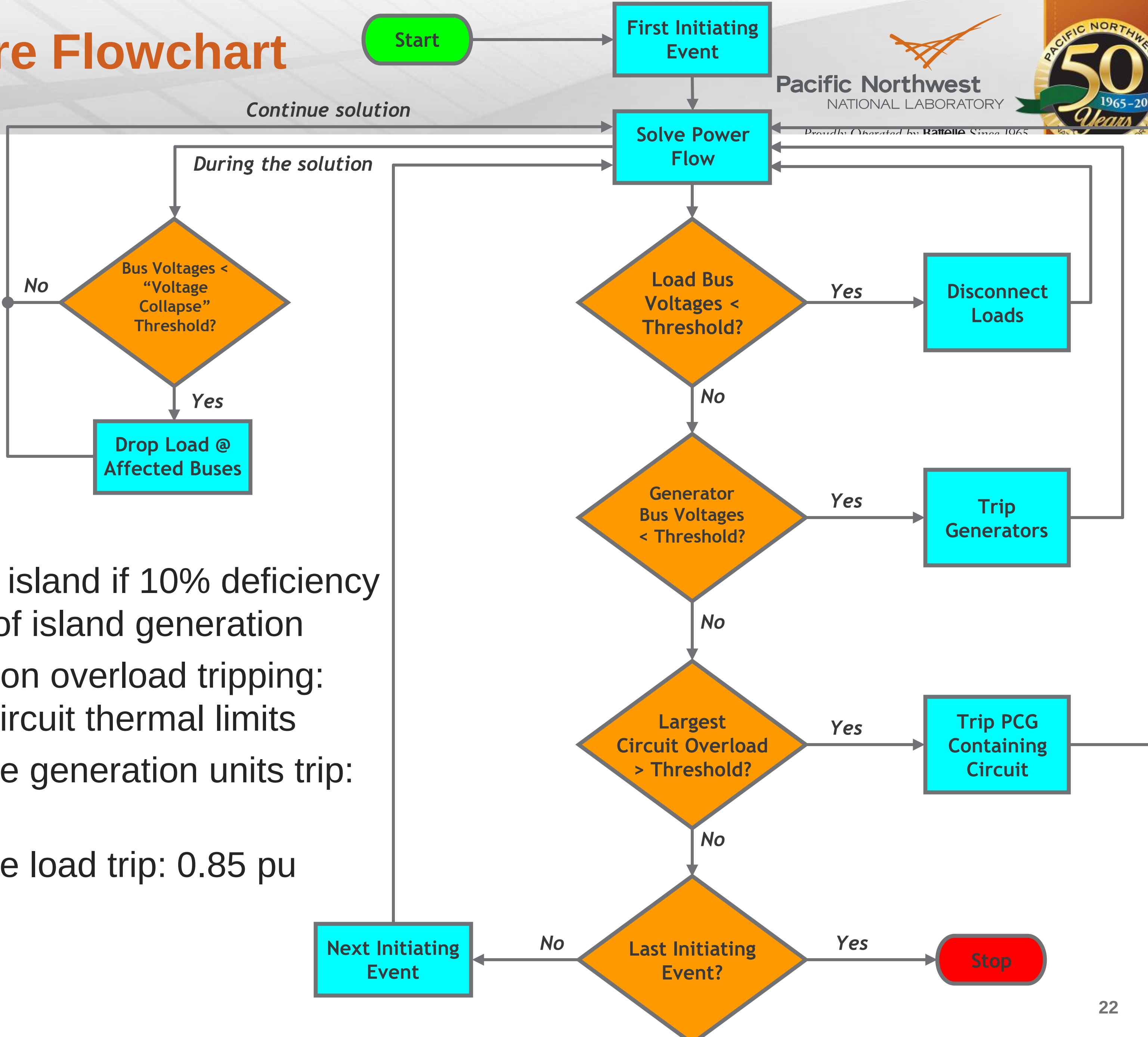


Steady-State Cascading Outage Analysis using TransCare

- Used TransCARE built-in logic for automated breaker placement.
- The breaker locations are utilized by TransCare to identify the Protection and Control Groups (PCGs) that a system component belongs to.
- During contingency solution, the dispatch algorithm restores generation-load balance in the system following the outage of a generating unit(s).
- Provided generation units participation factors are used to determine the new redispatch value for each generating unit.



TransCare Flowchart



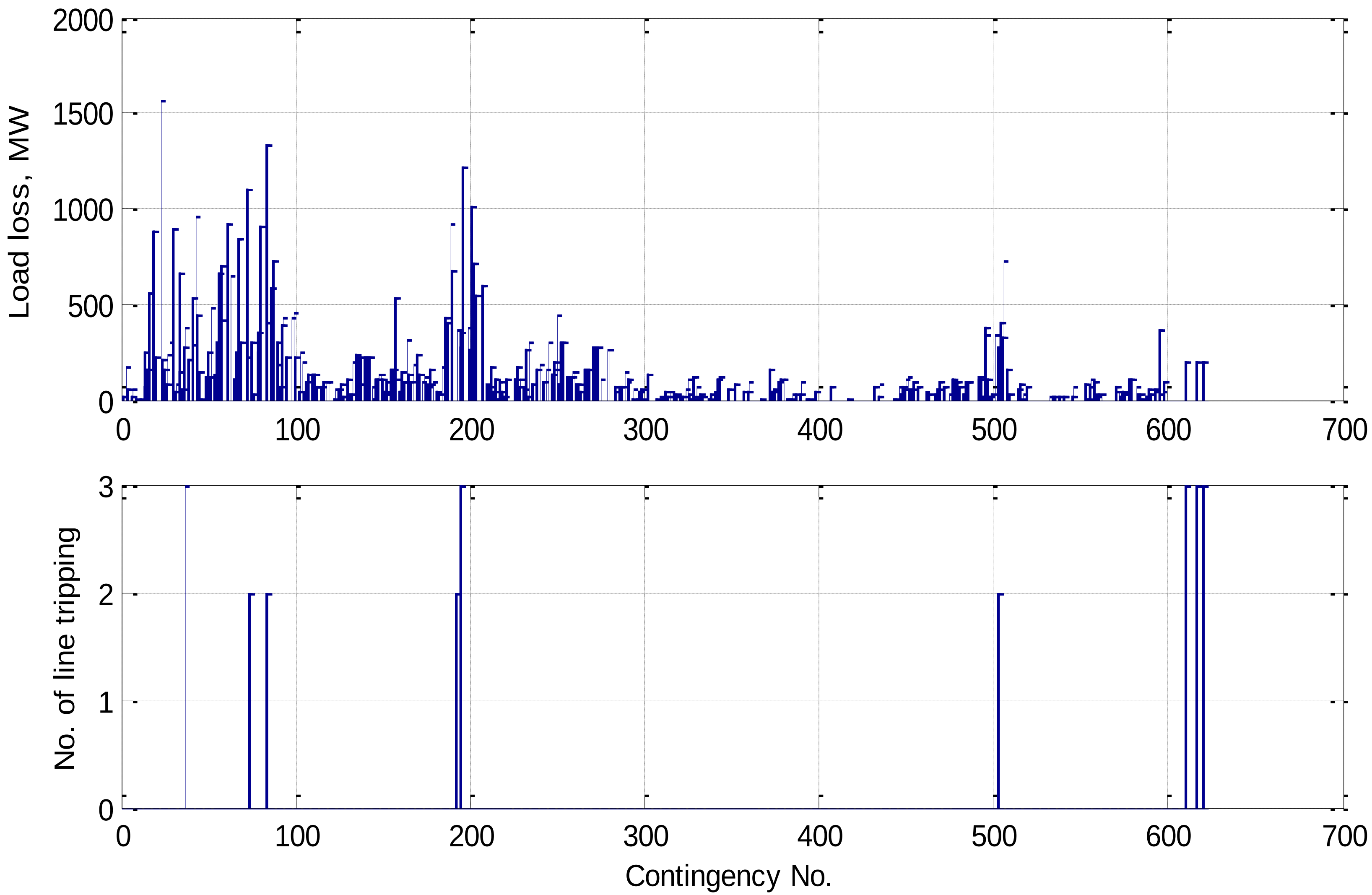
- Shut down island if 10% deficiency or excess of island generation
- Transmission overload tripping: 130% for circuit thermal limits
- Low voltage generation units trip: 0.85 pu
- Low voltage load trip: 0.85 pu

Summary of Results

- No. of initiating events: 620
- No. of Non-solved cases: 6 (1%)
- No. of Capacity Deficiency cases: 0%
- No. of Divergent cases: 0%
- No. of Non-solved cases after several power flows: 2 (0.3%)
- No. of Severe Cases with load loss or cascading events: 388 (62%)
- No. of normal cases: 224 (36%)
- Critical Event Corridor Identified

PCG1	PCG2	Frequency
PCG04490	PCG04489	5
PCG04026	PCG04490	3

TransCARE Cascading Outage Results



Other On-going Efforts

- Stakeholder outreach
- Parallelized DCAT using distributed processors and demonstrated on PNNL supercomputing facility
- Enhanced the DCAT code to make it user friendly, a manual is available with several test system examples
- Updated DCAT for PSS/E version 33
- Improved protection modeling and corrective actions (GMLC Extreme Events study)
  - Refine protection settings for distance relays and model Zone 3 protection
  - Use GAMS for corrective actions optimization
- Developing DCAT for Cascading-Outage Analysis for the Western Interconnection using GE PSLF (BPA TI project)

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- The project team appreciates technical support in using TransCARE from Murali Kumbale from Southern Company and Anish Gaikwad from the Electric Power Research Institute. Special thanks to the Electric Power Research Institute for providing a royalty-free copy of TransCARE to be used in this study.

Questions?

- Disclaimer: PNNL power industry partners in this project played only an advisory role. All models built and simulations were performed by PNNL staff. Consequently, all questions regarding this presentation should be only directed to the PNNL PI or PM with the contact information below.
- Samaan NA, JE Dagle, YV Makarov, R Diao, MR Vallem, TB Nguyen, LE Miller, B Vyakaranam, S Wang, FK Tuffner, and MA Pai. 2015. Dynamic Contingency Analysis Tool – Phase 1 . PNNL-24843, Pacific Northwest National Laboratory, Richland, WA.

http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24843.pdf

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