

Operational defense of power system cascading sequences: probability, prediction, & mitigation

James D. McCalley

Professor, Iowa State University

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With assistance from Qiming Chen and Kun Zhu

Disclaimer: Reference to any particular cascading scenario within these slides is based only on publicly available information and should not be viewed as conclusive in any sense with respect to that scenario.

Risk management: financial engineering, financial mathematics, portfolio analysis, decision analysis, market modeling.



Asset management: planning, operation, RCM, maximizing return, life extension, regulation compliance, condition monitoring, diagnostics.

Reliability: Generation adequacy, system reliability, probabilistic security

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IOWA STATE UNIVERSITY

Electric Power and Energy Systems Group



Iowa-Illinois Section
Iowa-Central Section



Overview

- ▶ Part A: Introductory material
- ▶ Part B: Identifying initiating events & their probabilities
- ▶ Part C: Assessment, detection, & corrective action determination
- ▶ Part D: Illustration

Part A:

Introduction

1. Orientation
2. Approach
3. A typical cascading process
4. Summary of cascading blackouts
5. Assumptions
6. Terminology
7. Event-probability space

Orientation

- ▶ Unreasonable to claim “never again”; Goal is to reduce frequency, mitigate severity
- ▶ Addressing cascading transmission failures, NOT common mode distribution failures (Isabel)
- ▶ A comprehensive effort includes innovations in tools, and training in using those tools to build confidence in the individuals responsible for decision-making, in regards to:
 - Design: transmission, generation, control, protection
 - Maintenance: optimal allocation of resources
 - Operation, preventive
 - Operation, corrective
 - Restoration
 - Blackout re-creation
- ▶ We focus on operational innovations

Approach to blackout mitigation

Preventive control is for “high”-probability events.
Corrective control is for “not-high” probability events.
Blackouts typically result from the latter.

Corrective control is operational solution to blackouts.

Approaches include the following options:

- Response-based action (UFLS, UVLS) or **event-based**
- Actions determined off-line (today’s SPS) or **on-line**,
after event, or **in anticipation of event**
- Automatic, or **actuated through operator**

→ The approach is corrective control, event based, with actions determined on-line via anticipatory computing, as decision support for the operator.

A typical cascading process

- 1. Initiating event: One or several components trip because of fault and/or other reasons;**
- 2. Steady-state progression (slow succession):**
 - a. System stressing: heavy loading on lines, xfmrs, units**
 - b. Successive events: Other components trip one by one with fairly large inter-event time intervals**
- 3. Transient progression in fast succession:**
 - a. Major parts of system goes under-frequency and/or under-voltage.**
 - b. Components begin tripping quickly**
 - c. Uncontrolled islanding and wide spread blackout.**

Let's look (cautiously) at the August 14 outage, with the important qualifier that no firm conclusions may be made yet...

INITIATING
EVENTS ???

3:05 Harding-Chamberlain 345 kV
 3:32 Hanna-Juniper 345 kV
 3:41 Star-South Canton 345 kV
 3:45 Canton Central-Tidd 345 kV
 4:06 Sammis-Star 345 kV

STEADY-STATE
PROGRESSION

4:08:58 Galion-Ohio Central-Muskingum 345 kV
 4:09:06 East Lima-Fostoria Central 345 kV
 4:09:23-4:10:27 Kinder Morgan (rating: 500 MW; loaded to 200 MW)
 4:10 Harding-Fox 345 kV
 4:10:04 – 4:10:45 20 generators along Lake Erie in north Ohio, 2174 MW
 4:10:37 West-East Michigan 345 kV
 4:10:38 Midland Cogeneration Venture, 1265 MW
 4:10:38 Transmission system separates northwest of Detroit
 4:10:38 Perry-Ashtabula-Erie West 345 kV
 4:10:40 – 4:10:44 4 lines disconnect between Pennsylvania & New York
 4:10:41 2 lines disconnect and 2 gens trip in north Ohio, 1868 MW
 4:10:42 – 4:10:45 3 lines disconnect in north Ontario, New Jersey, isolates NE part
 of Eastern Interconnection, 1 unit trips, 820 mw
 4:10:46 – 4:10:55 New York splits east-to-west. New England and Maritimes
 separate from New York and remain intact.
 4:10:50 – 4:11:57 Ontario separates from NY w. of Niagara Falls & w. of St. Law.
 SW Connecticut separates from New York, blacks out.

TRANSIENT
PROGRESSION

Summary of cascading blackouts

Location	Date	MW Lost	Collapse time	#successive events
US-NE	11/9/1965	20000	13 minutes	Many
US-NE	7/13/1977	6000	1 hour	Many
France	1978			
Sweden	1983			
US-West	1/17/1994	7500	1 minute	3
US-West	12/14/1994	9336		
US-West	7/2/1996	11743	36 seconds	Several
US-West	7/3/1996	1200	> 1 minute	Prevented by fast op. action
US-West	8/10/1996	30489	> 6 minutes	Many
US-central	6/25/1998	950		
Brazil	3/11/1999	25000	30 seconds	substation topology
India	1/2/2001	12000		
US-NE	8/14/2003	62000	> 1 hour	Many
UK	8/28/2003	724	8 seconds	
Denmark/Swede	9/23/2003			
Italy	9/28/2003	Very large	Slow	

Assumptions

- ▶ Progression can be arrested if right action(s) are taken during period of steady-state progression
- ▶ Unpredictability localized in the initiating event
- ▶ Successive events are predictable given initiating event.
- ▶ Preventive control ensures that system performance for high-probability initiating events is acceptable

Terminology

Initiating event

- ▶ A disturbance consisting of first-disturbance followed by outage of one or more components; may include protection failure

Probability order

- ▶ Order 1: Probability of single element outage in next hr: $P=10^{-5}$
- ▶ Order 2: Probability of 2 independent outages: $P^2=10^{-10}$
- ▶ Order 3: Probability of 3 independent outages: $P^3=10^{-15}$
- ▶ Order=number of independent events
- ▶ Provides probability scale in considering initiating event likelihood
- ▶ Dependencies between events result in higher probabilities: $P(A \cap B) = P(A)P(B|A)$.

N-k initiating events

- ▶ It is implicit that $k > 1 \rightarrow$ initiating events with loss of multiple elements
- ▶ Most N-1 events are order 1. N-k events may be order 1 to order k.

Successive events

- ▶ Significant changes in configuration/conditions occurring after initiating event.
- ▶ Assumed to be predictable with advanced simulator modeling
- ▶ Limited to as-designed protection acting under stressed conditions to trip element
 - Generator protection: field winding overexcitation, loss of field, loss of synchronism, overflux, overvoltage, underfrequency, and undervoltage
 - Transmission protection: impedance, overcurrent backup, out-of-step

Event-probability space

- Probability space: the space of all possible initiating events



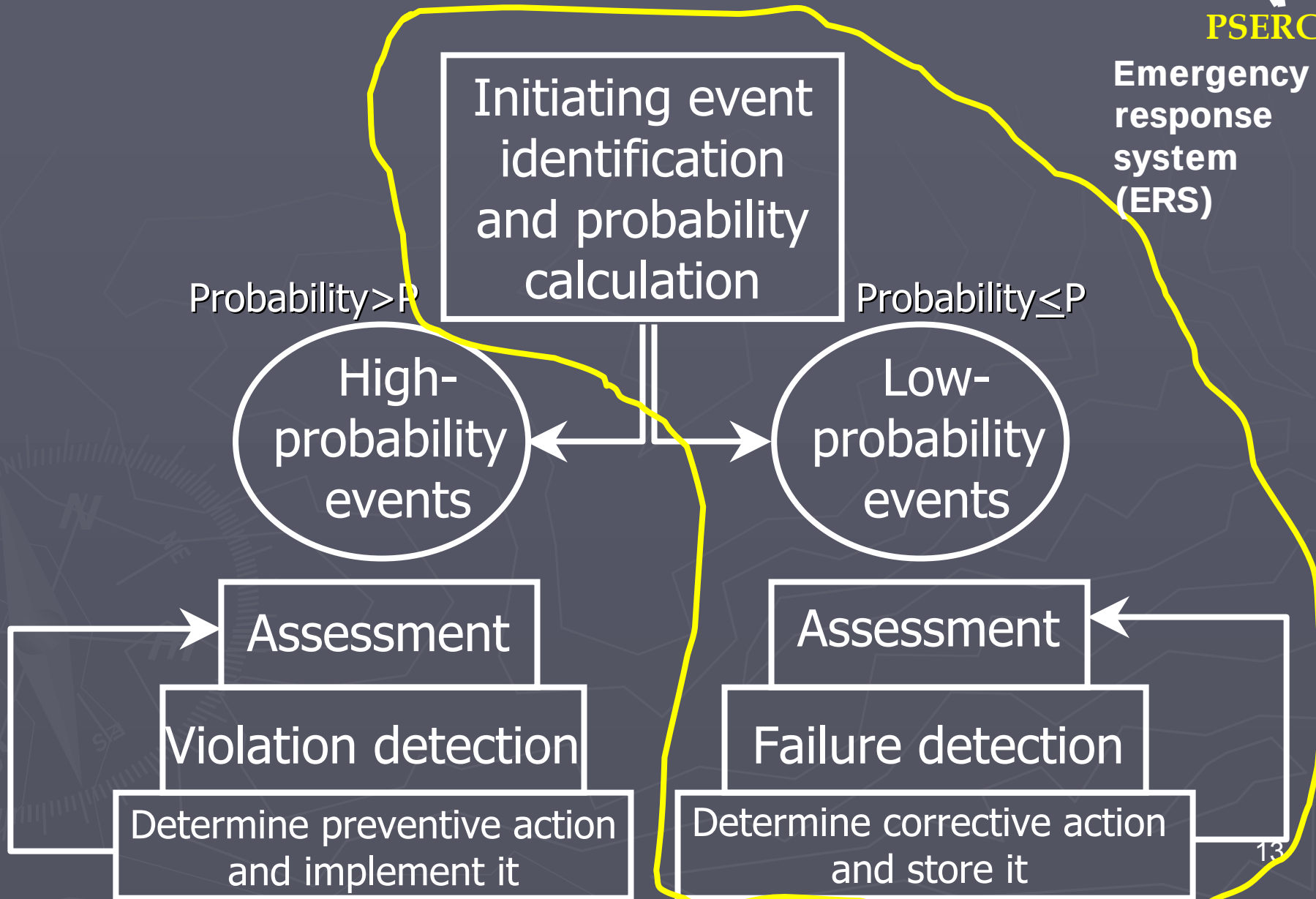
- Construct response plans for each initiating event so that operator is "ready" in case that initiating event occurs.
- Approach: Prepare response plans for initiating events resulting in failure, according to decreasing probability of initiating event, so as to maximize "operator readiness."
- Assume successive events are predictable given initiating event

Preventive/corrective action paradigm

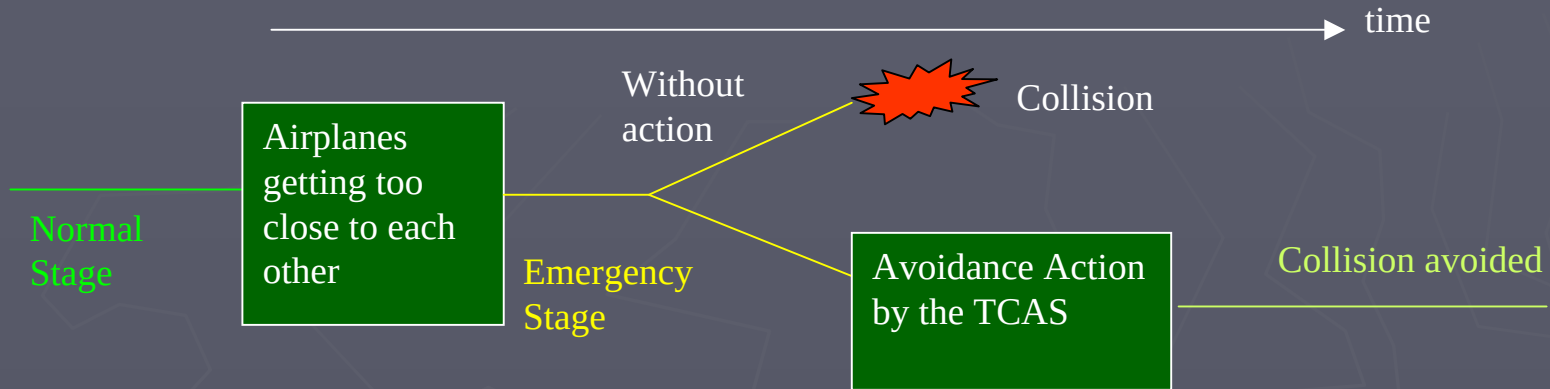


PSERC

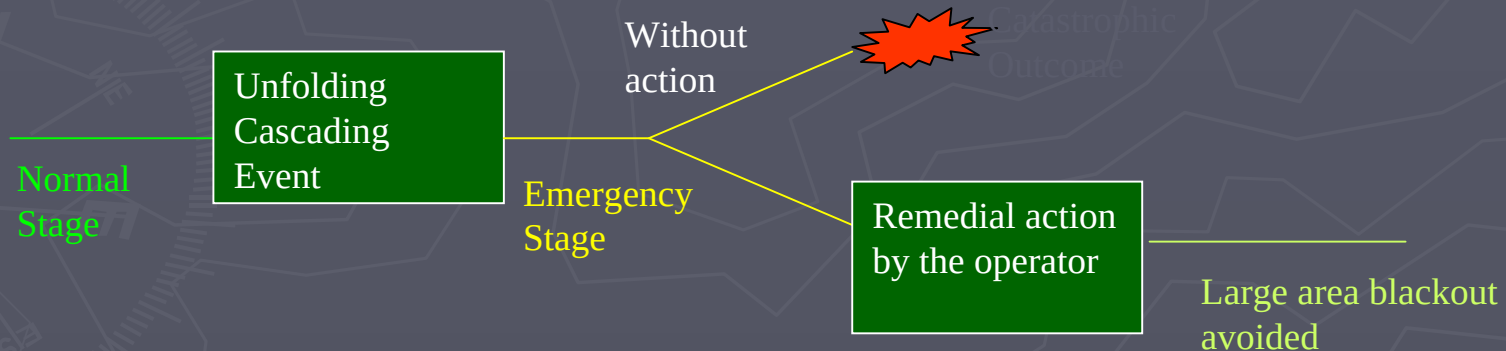
Emergency
response
system
(ERS)



An Analogy to Air Traffic Control

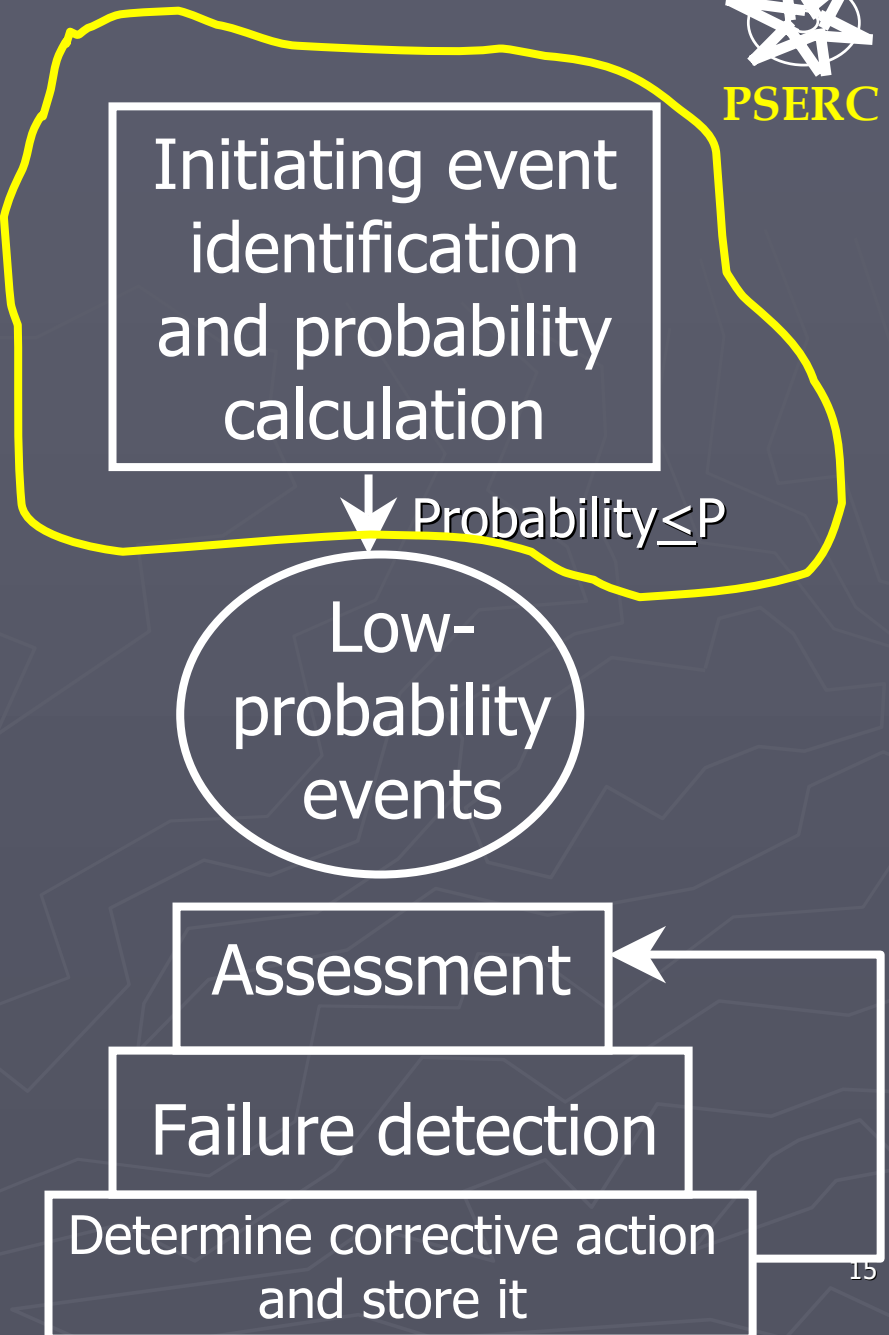


Traffic Alert and Collision Avoidance System



Emergency Response System

Part B: Identifying initiating events and their probabilities



Identifying initiating events and their probabilities

2 kinds of initiating event probability models:

1. Statistical models
2. Component model

Point of emphasis:

- In preventive action, we want initiating event probabilities to guide how to preventively operate system.
- In corrective action, we want them in order to answer "what to compute next."

N-K statistics

From Adler, et al, “*An IEEE survey of US and Canadian overhead transmission outages at 230 kV and above,*” 1994

Cont.	N-1	N-2	N-3	N-4	N-5	N-6	N-7	N-8
Total No	10143	951	143	36	8	5	1	3

- The survey are for years between 1965 and 1985
- The N-k contingencies happen within one minute
- The table above are pooled for all voltage levels

Three statistical models with maximum likelihood parameter estimation

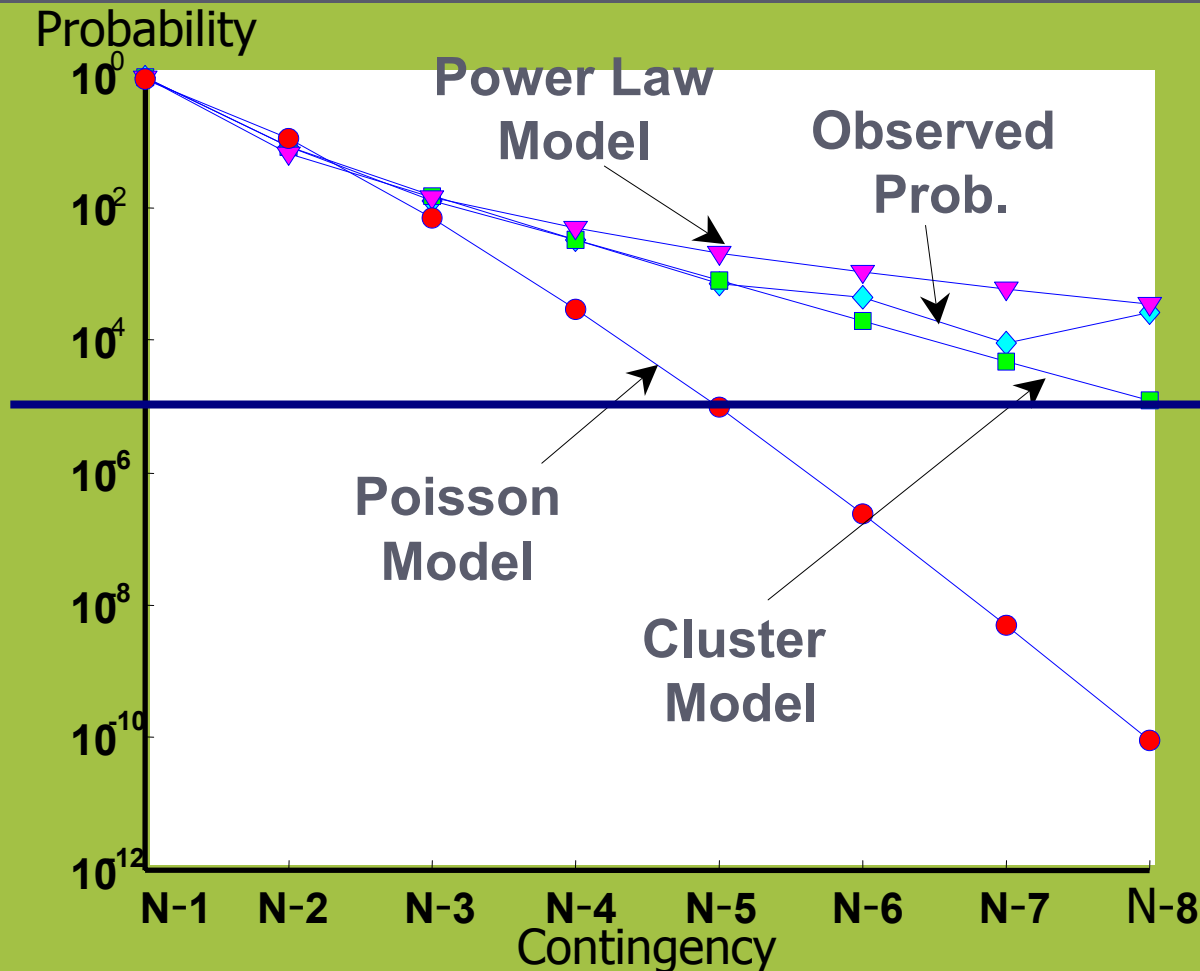
Below gives probability of x components outaged given occurrence of an event.

$$\Pr(X = x | \alpha = 3.115, \mu = 1.12657) = \binom{3.115^{-1} + x - 2}{x-1} \times \left(\frac{1.1266 - 1}{1.1266 - 1 + 3.115^{-1}} \right)^{x-1} \times \left(\frac{3.115^{-1}}{1.1266 - 1 + 3.115^{-1}} \right)^{3.115^{-1}} \quad \text{for cluster model}$$

$$\Pr(X = x | \lambda = 0.12657) = e^{-0.12657} 0.12657^{x-1} / (x-1)! \quad \text{for poisson model}$$

$$\Pr(X = x | p = 3.78) = 0.9098x^{-3.78} \quad \text{for power law model}$$

Comparison of different statistical models for N-k contingencies



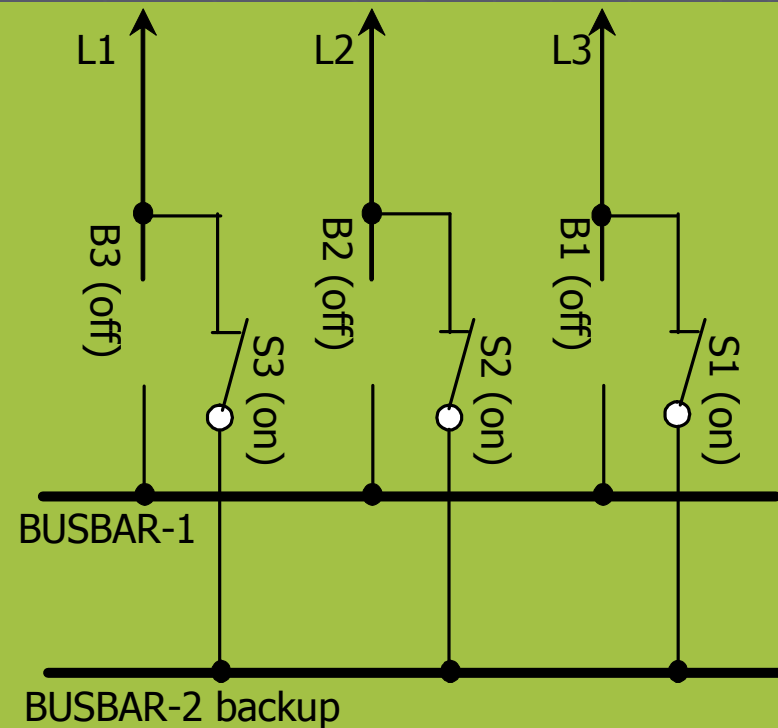
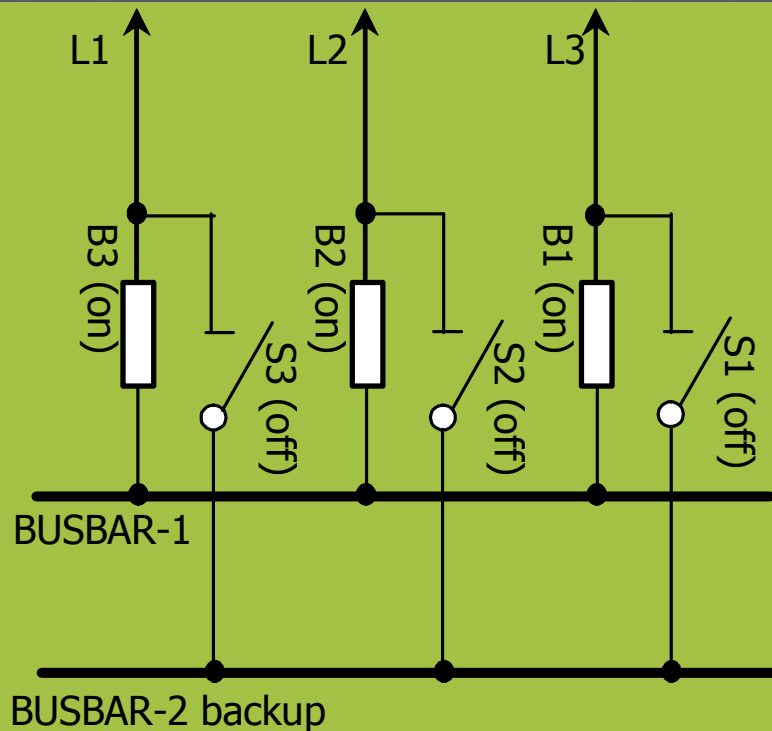
Conclusions:

1. "Heavy-tail" of observed probability implies high-order events more likely.
2. Power law overestimates & Poisson underestimates. Cluster model is statistically better than power law.

Component model for probability estimation

- ▶ Traditional event identification uses bus-branch characterization of network topology.
- ▶ But substation topology influences probabilities
- ▶ Developed systematic method for using breaker-switch data (as input to EMS topology processor) to identify N-k events & probabilities

N-3 Exposure increases from P^2 to P when performing maintenance on a double breaker-double bus configuration



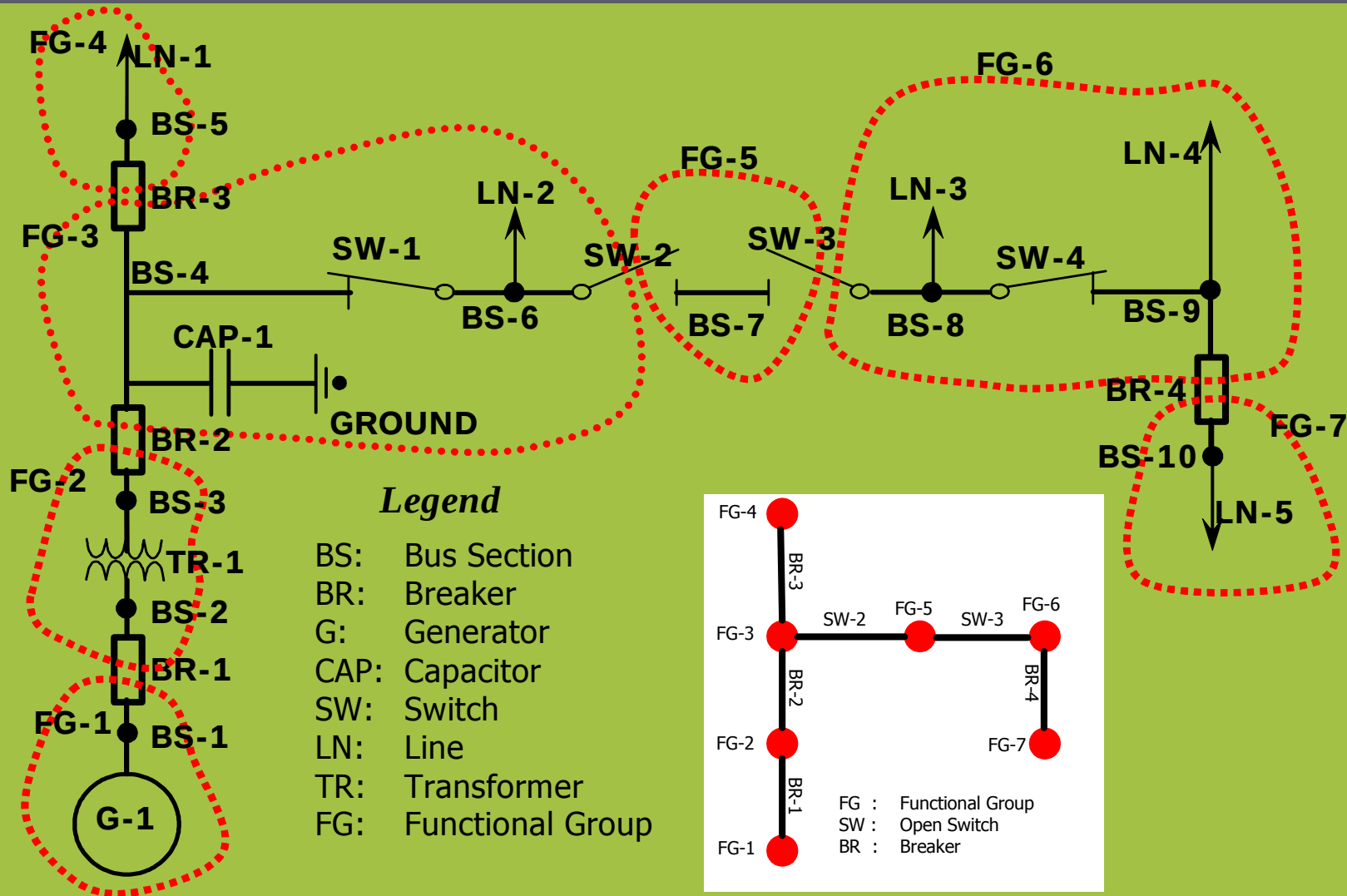
Component model

Definition: A functional group is a group of components that operate & fail together as a result of breaker locations within the topology that interconnects them.

We admit five types of initiating events:

1. Functional group tripping, $\sim P$
 - Proper relay tripping, may trip multiple components
2. Fault plus breaker failure to trip, $\sim P^2$
 - Breaker stuck or protection fail to send the signal to open
 - Two neighboring functional groups tripped
3. Inadvertent tripping of two or more components, $\sim P^2$
 - Inadvertent tripping of backup breaker to a primary fault
4. Common mode events, $\sim P$
 - Common right of way, common tower.
5. Any of the above together with independent outage of any other single component in a selected set, $\sim P^2 \rightarrow \sim P^3$

Functional group decomposition





Component model initiating events & probabilities

Functional group (FG) decomposition provides for efficient initiating event identification and probability computation.

Each FG defines initiating event of losing all components in the FG

$$P_{removal}^{FG_i} = \sum_{C_j \in FG_i} P_{failure}^{C_j}$$

Each breaker & 2 FGs it joins defines initiating event of losing all components in both FGs

$$P_{fault\ stuck}^{B_{ij}} = \left(P_{fault}^{FG_i} + P_{fault}^{FG_j} \right) \times P_{per\ demand}^{B_{ij}}$$

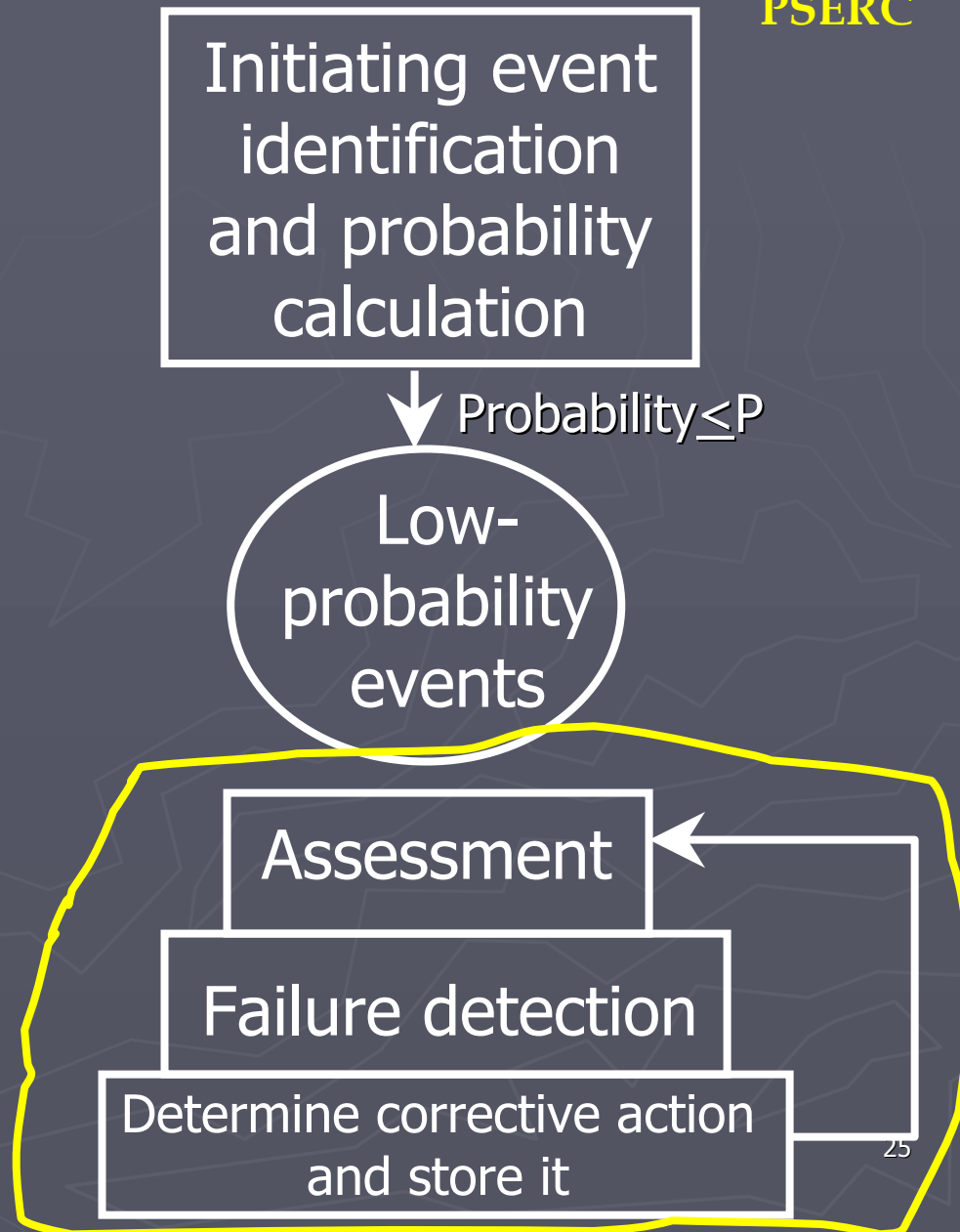
Each FG defines initiating event of losing all components in FG plus those lost due to operation of backup protection

$$P_{inadvertent}^{FG_k \cap B_{ij}} = P_{fault}^{FG_k} \times P_{per\ demand\ on\ FG_k}^{B_{ij}}$$

Part C: Assessment, detection, & corrective action determination

Dynamic Event Tree (DET)

- DET attributes
- DET construction



DET attributes

- ▶ Tree-like structures comprised of nodes and arcs
- ▶ Nodes are “set of equivalent states” (set of system states that similarly respond to certain events); branches are events; root is pre-initiating event state; branch from root is initiating event
- ▶ Path from root to end node represents discrete sequence;
→ represents “slow” blackouts very well
- ▶ Dynamic because network configuration & operating conditions change with time; so does root node & tree structure
- ▶ A conceptual way to organize interaction between conditions, events, actions; a compact means for storing large number of simulations & efficiently retrieving them for operator use

- Randomness is in initial events
- Successive events are “as designed” protection actions captured by simulator

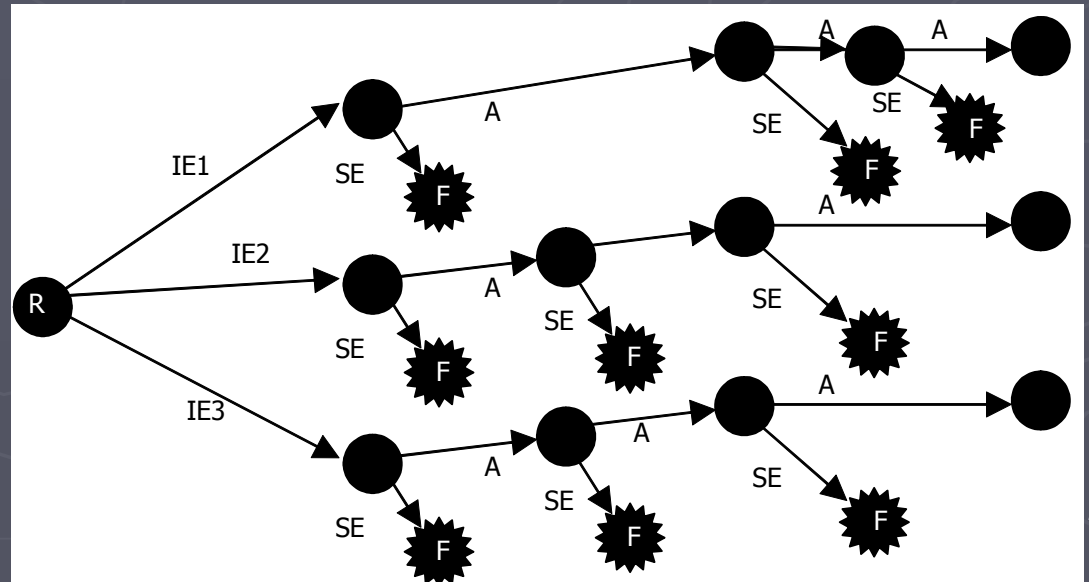
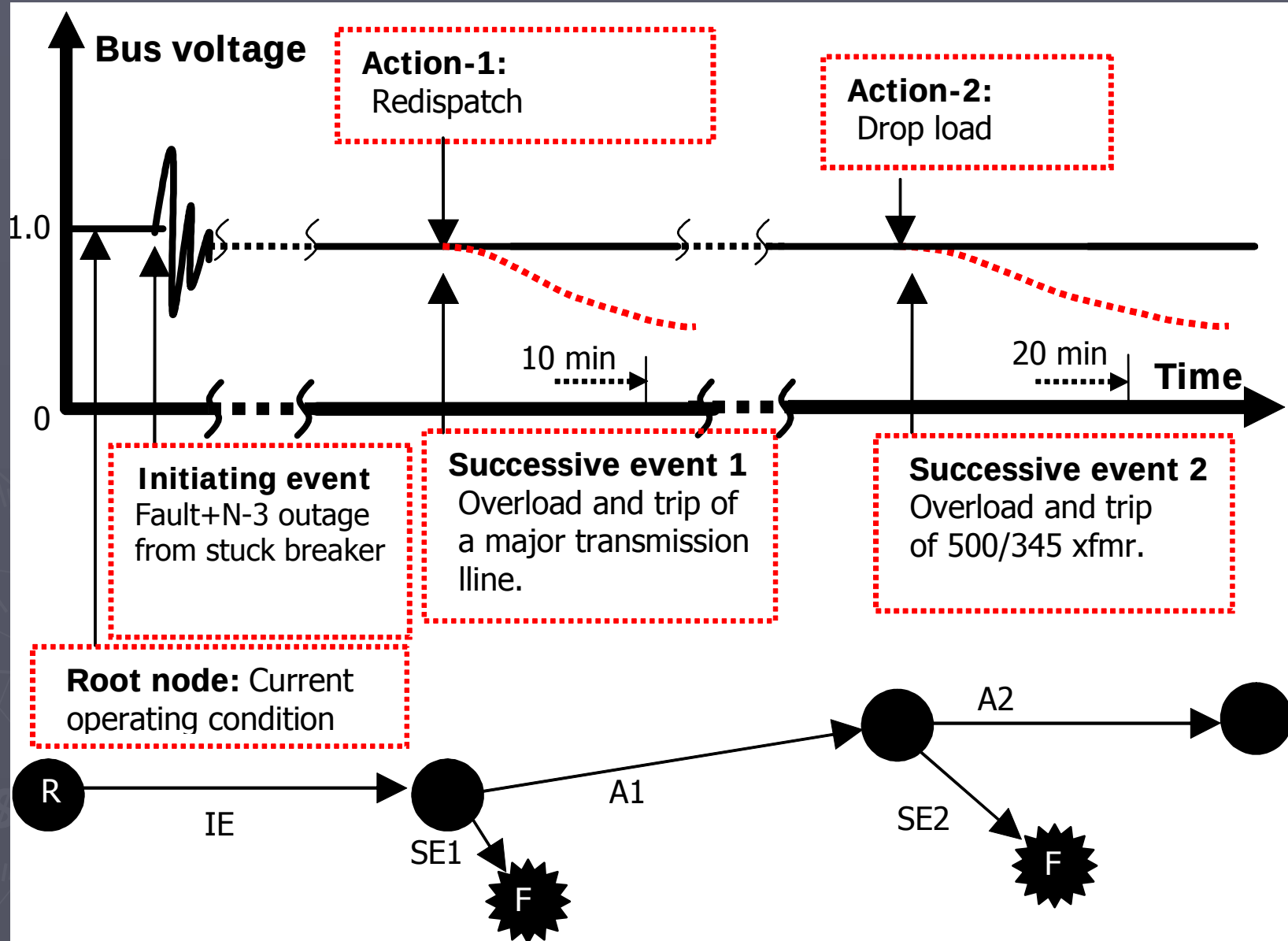


Illustration of DET construction



DET construction: simulation

- ▶ Seamless integration with real time information, including switch-breaker data for automatic initiating event identification
- ▶ Model full range of dynamics:
 - Fast dynamics, including generator, excitation, governor
 - Slow dynamics, including AGC, boiler, thermal loads
- ▶ Model condition-actuated protection action that trips element
 - Generator protection: field winding overexcitation, loss of field, loss of synchronism, overflux, overvoltage, underfrequency, and undervoltage
 - Transmission protection: impedance, overcurrent backup, out-of-step
- ▶ Capability of saving & restarting from conditions at any time
- ▶ Fast, long-term simulation capability:
 - Simulate both fast and slow dynamics with adaptive time step using implicit integration method
 - Utilize sparsity-based coding
 - Deployable to multiple CPUs
- ▶ Intelligence to detect and prevent failures

DET construction: failure detection & prevention

► Failure detection:

- Activation of any protection that would trip an additional component
- Detection of an overload, underfrequency, or undervoltage condition exceeding tolerable thresholds

► Failure prevention:

- Expert system with multiplicity of possible actions taken based on failure type detected
- Or a simple and robust optimization to identify action for relieving overloads.

Redispatch/interrupt to alleviate overloads



A linear program spawned by the simulator whenever an increasing line loading exceeds a specified threshold.

Maximize:

$$\text{TotalServedLoad} = \sum \text{PLoad}$$

Subject to:

$$0 < [\text{Pgen}] < [\text{Pgenmax}] \text{ for each bus}$$

$$0 < [\text{PLoad}] < [\text{PLoadmax}] \text{ for each bus}$$

$$-[\text{Plinerating}] < [\text{Pline}] < [\text{Plinerating}] \text{ for each branch}$$

$$[\text{Pgen} - \text{PLoad}] = [\text{B}'][\theta]$$

$$[\text{Pline}] = [\text{Bus Branch Incidence Matrix}][\text{Diag}(1/\text{XB})][\theta]$$

Output is identification of redispatch generators and amounts and/or load interruption buses and amounts

DET Construction

Computing paradigms:

A. High-level computing paradigm: Tree construction occurs continuously with as much computing power as available.

B. Two lower level computing paradigms:

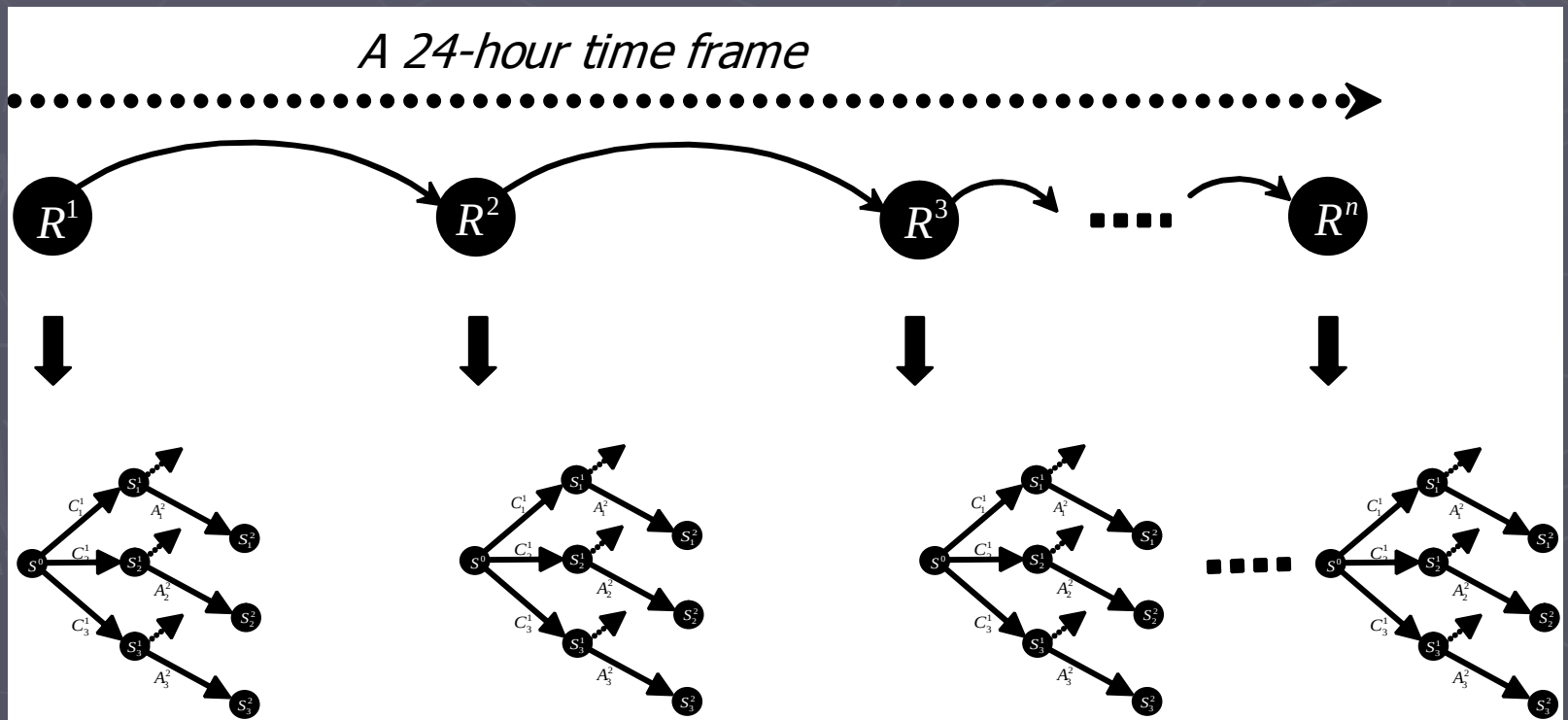
1. *Day-ahead computing* : Create tree for every unique state, as forecasted, in next 24 hours.
2. *Archived computing* : DETs are stored, continuously retrieved, updated, & extended. This approach offers a way to maintain decision support even for extremely rare events ($P < P^4$).

The above two paradigms are complementary; we limit discussion to only the first one for this presentation.
(But the second one has significant potential.)



Day ahead DET algorithm

- Step 1: run no-contingency simulation for next 24 hr period
- Step 2: discretize 24-hours into limited number of root states
- Step 3: generate initiating events for each root state
- Step 4: For each root state, generate a DET
- Step 5: Store all DET's in database





DET real-time information flow

Weather Elements:

- Lightning
- Precipitation
- Wind
- Temperature

EMS Information:

- System component parameters
- System topology
- Protection logic & settings

DET Engine Functions:

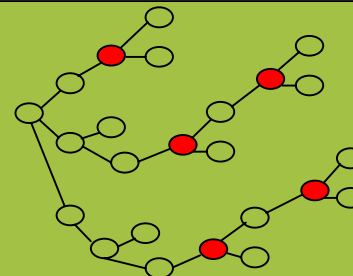
- System state (power flow solution, breaker-switch status data, and network topology)
- Initiating event identifier and probability estimator
- Successive event identified
- Action identifier
- Simulator

Load Forecast:

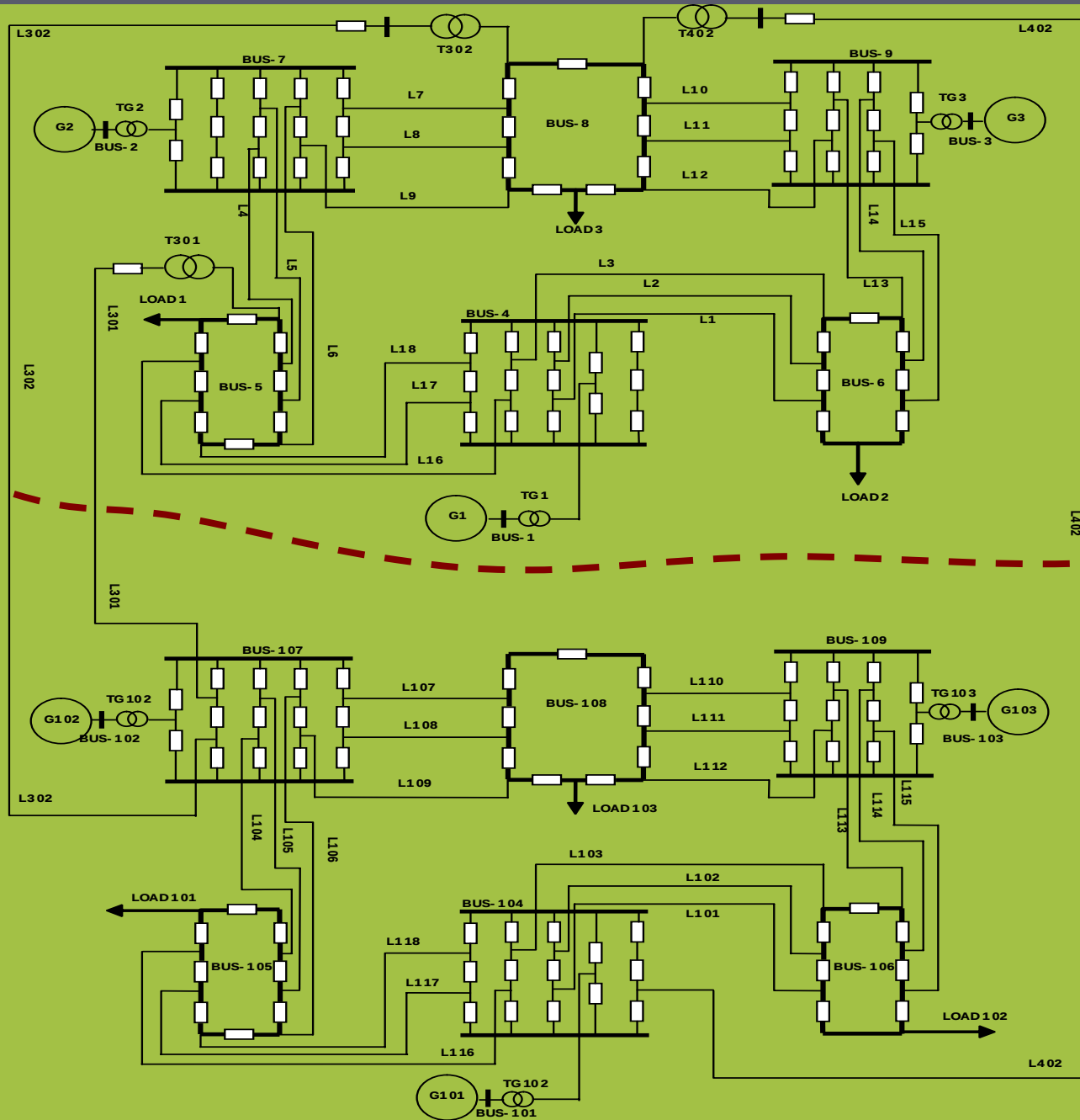
- Near Term Day Ahead Load Forecast

Day Ahead System Configuration Schedule:

- Lines
- Transformers
- Loads
- Shunts
- Generators
- Breaker
- Switches



Part D: Illustration

Upper
Area60MW
↑Lower
Area

6 Generators
 9 transformers
 36 lines
 12 substations
 129 breakers
 6 Loads
 3 Tie lines

Total load
 630 MW
 Upper Area Load
 378 MW
 Lower Area Load
 252 MW
 Upper Area Gen
 318MW
 (max 525MW)
 Lower Area Gen
 318MW
 (max 525MW)

DET test scenario & initiating event summary

- ▶ Load ramps 20% from 900sec to 2700sec
- ▶ Line loadings are monitored; most effective redispatch & interruption actions are identified for overloaded lines

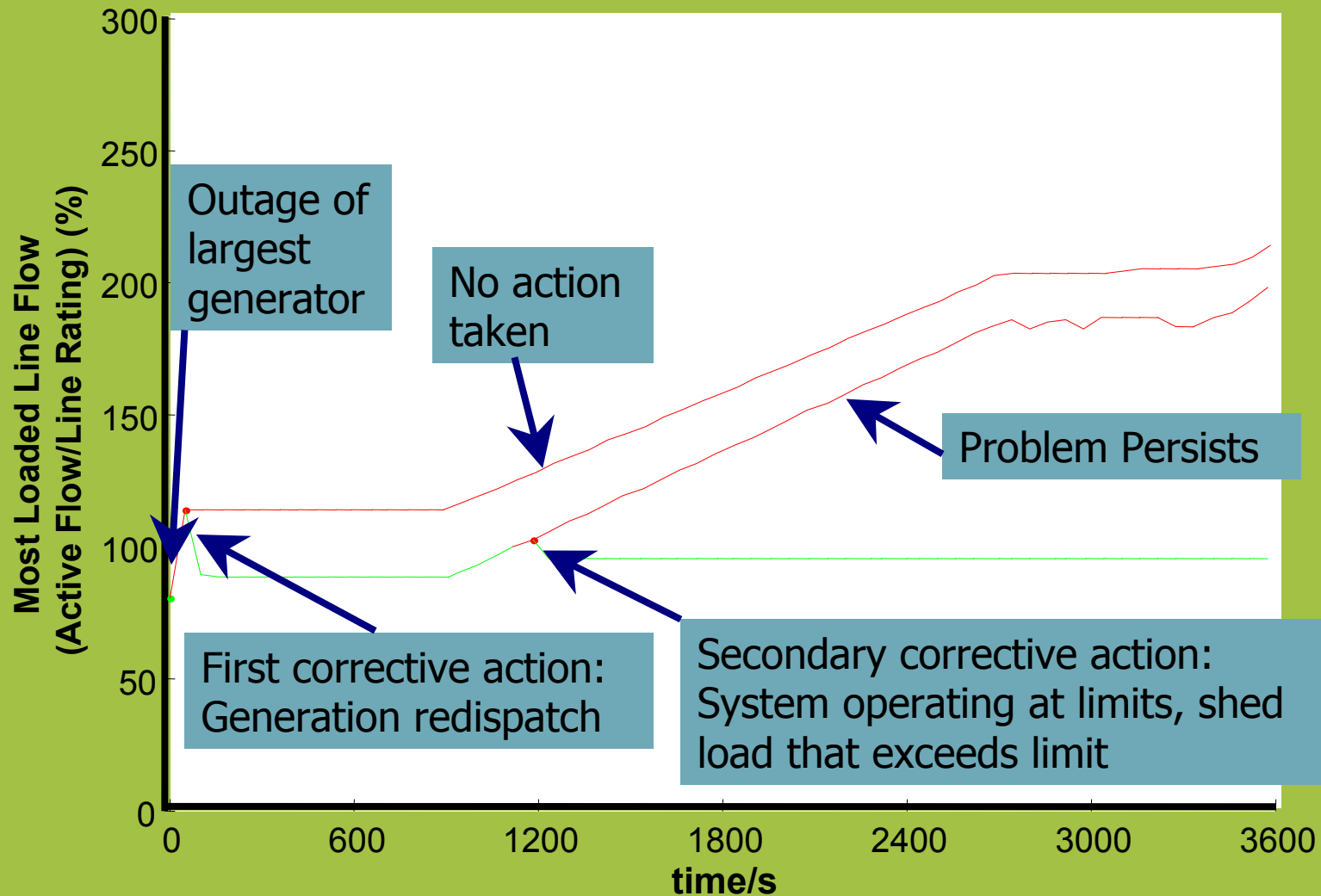
Initiating event* category	Total	N-1	N-2	N-3
Functional group removal	71	71	0	0
Stuck breaker (two neighboring FGs)	119	52	67	0
Inadvertent tripping	187	0	153	34
Total	337	123	220	34

*Did not include consideration of additional independent event set.

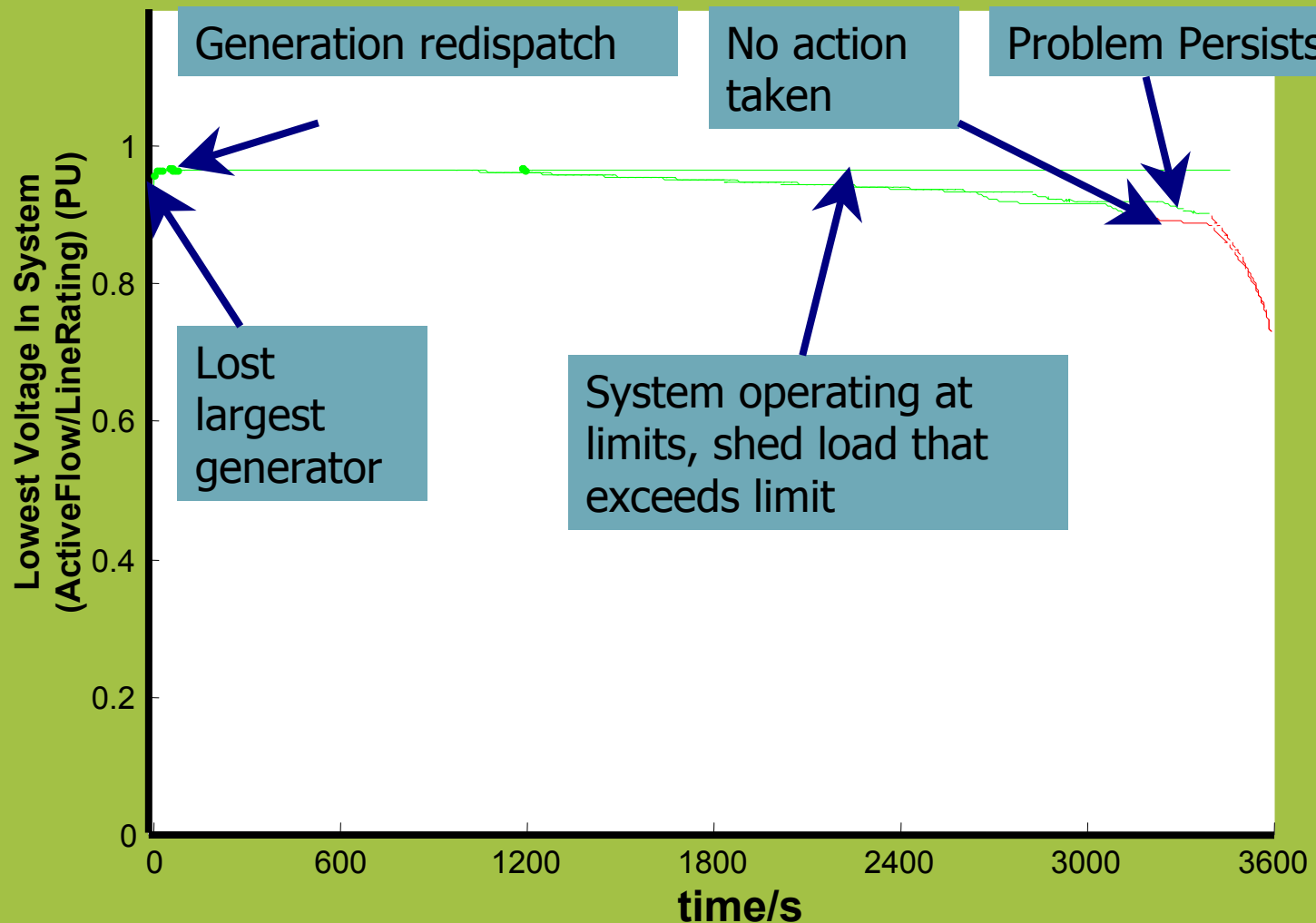
Dynamic Decision-Event Tree

Most Loaded Line Flow For FG Tripping Contingency

Lost of Largest Generator in upper area



Dynamic Decision-Event Tree
Voltage Response For FG Tripping Contingency
Lost of Largest Generator in upper area



Final Comments

- ▶ The approach described makes sense.
 - Preparing operators for rare events is fundamental to operating engineering systems having catastrophic potential; it has precedent in air traffic control, nuclear, & process control.
 - It is a generalization of already-existing event-based special protection systems, except here
 - ▶ response is continuously developed on-line instead of off-line,
 - ▶ actuation is done through a human (slower, but more flexible)
- ▶ Proper training to build operator confidence is essential.
- ▶ It should be implemented in concert with additional innovation and training in design, maintenance, preventive control, and restoration.