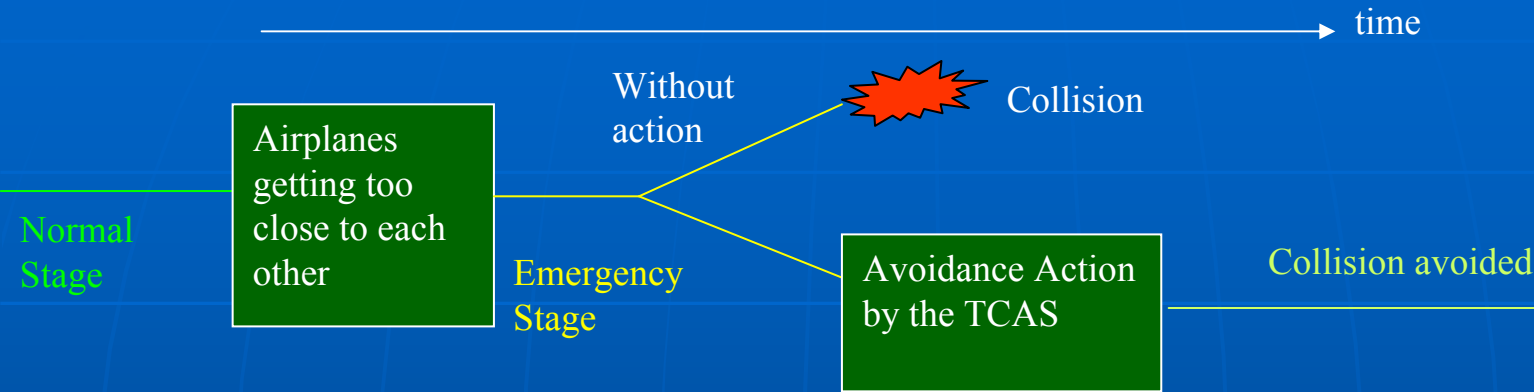


Operational Defense of Power System Cascading Outages (Project S-26)

James McCalley and Siddhartha Khaitan
Department of Electrical and Computer
Engineering
Iowa State University
PSERC Tele-Seminar, April 15, 2008

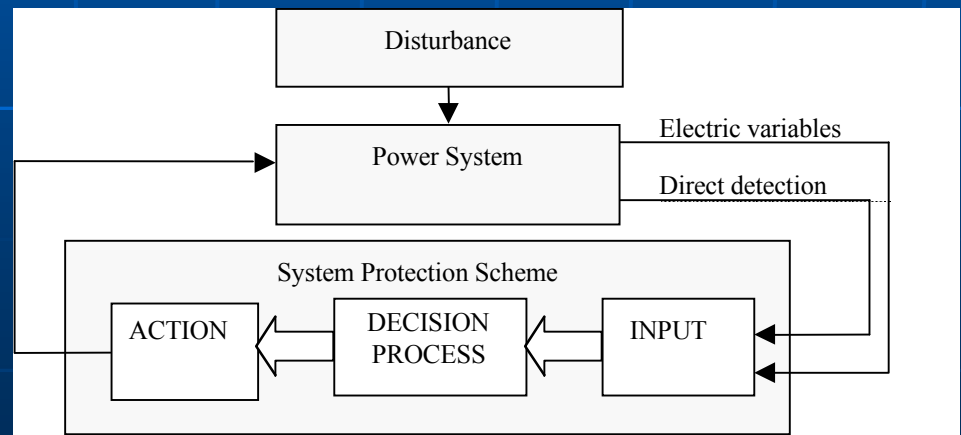
Analogies



Traffic Alert and Collision Avoidance System



Emergency Response Information System



Automation of SPS Design

Research Problem Statement

*“to provide operators with a **very fast** (**online**) computational capability to predict system response and identify corrective actions through analytical modeling and **fast** numerical simulation studies for low probability, high-consequence catastrophic events, by exploiting the state of the art in software and hardware”*

Today's Seminar

- Historical perspective of cascading events in past 40 years
- N-k contingency selection
- Assessment, Detection and Control action Determination
- DFS Based Island Detection and Simulation
- Numerical Methods
- Archrivals

Recent Blackouts in Power Systems

IMPACT

Location	Date	MW Lost	Duration	People affected	Approximate cost
US-NE	11/9/1965	20000	13 hours	30 million	
US-NE	7/13/1977	6000	22 hours	3 million	300 million
France	12/19/1978	30000	10 hours		
West Coast	12/22/1982	12350		5 million	
Sweden	12/27/1983	> 7000	5.5 hours	4.5 million	
Brazil	4/18/1984	15762			
Brazil	8/18/1985	7793			
Hydro Quebec	4/18/1988	18500			
US-West	1/17/1994	7500			
Brazil	12/13/1994	8630			
US-West	12/14/1994	9336		1.5 million	
Brazil	3/26/1996	5746			
US-West	7/2/1996	11743		1.5 million	
US-West	7/3/1996	1200		small number	
US-West	8/10/1996	30489		7.5 million	1 billion dollars
MAPP, NW Ontario	6/25/1998	950	19 hours	0.152 million	
San Francisco	12/8/1998	1200	8 hours	1 million	
Brazil	3/11/1999	25000	4 hours	75 million	
Brazil	5/16/1999	2000			
India	1/2/2001	12000	13 hours	220 million	107 million
Rome	6/26/2003	2150		7.3 million	
US-NE	8/14/2003	62000	1-2 days	50 million	4-6 billion
Denmark/Sweden	9/23/2003	6300	6.5 hours	5 million	
Italy	9/28/2003	27000	19.5 hours	57 million	
Croatia	12/1/2003	1270 mwh			2.5 million
Greece	7/12/2004	9000	3 hours	5 million	
Moscow/Russia	5/24-25/2005	2500	>6 hours	4 million	
European Blackout	11/4/2006	> 6400	1 Hour	15 million	

PRE-COLLAPSE EVENTS	Location	Date	Generation trip	Transmission trip	Time between initiating and secondary, pre-collapse events
	US-NE	11/9/1965	no	Four 230KV lines	few minutes
	US-NE	7/13/1977	Yes	Yes	occurred in a sequence between 20 to 45 minutes after initial event
	France	12/19/1978		yes	> 30 minutes
	West Coast	12/22/1982	No	Yes	Fast
	Sweden	12/27/1983	No	Yes	50 seconds
	Brazil	4/18/1984	Xmer	yes	9-10 minutes
	Brazil	8/18/1985	No	yes	
	Hydro Quebec	4/18/1988	Transformer	yes	2-3 seconds
	US-West	1/17/1994	Yes	Yes	Fast
	Brazil	12/13/1994	yes	yes	
	US-West	12/14/1994	No	Yes	40-52 seconds
	Brazil	3/26/1996	Xmer	Yes	
	US-West	7/2/1996	yes	yes	20 seconds
	US-West	7/3/1996	No	yes	fast
	US-West	8/10/1996	yes (13 generators)	yes	5-7 minutes
	MAPP, NW Ontario	6/25/1998	No	yes	44 minutes
	San Francisco	12/8/1998	yes	yes	16 seconds
	Brazil	3/11/1999	No	Yes	> 30 seconds
	Brazil	5/16/1999	No	Yes	
	India	1/2/2001			
	Rome	6/26/2003	No	No	
	US-NE	8/14/2003	yes	yes	more than 2 hours
	Denmark/Sweden	9/23/2003	yes	yes	5 minutes
	Italy	9/28/2003	No	Yes	25 minutes
	Croatia	12/1/2003	Yes	Yes	30 seconds
	Greece	7/12/2004	Yes	No	10 minutes
	Moscow/Russia	5/24-25/2005	No	Yes	>12 hours
	European Blackout	11/4/2006	yes	Yes	30 minutes
					7

COLLAPSE TIME & NO. OF SUCCESSIVE EVENTS

Location	Date	Collapse time	#successive events
US-NE	11/9/1965	13 minutes	Many
US-NE	7/13/1977	1 hour	Many
France	12/19/1978	> 30 minutes	Many
West Coast	12/22/1982	few minutes	Many
Sweden	12/27/1983	> 1 minute	Many
Brazil	4/18/1984	> 10 minutes	Topology
Brazil	8/18/1985		Topology
Hydro Quebec	4/18/1988	< 1minute	Many
US-West	1/17/1994	1 minute	3
Brazil	12/13/1994		many
US-West	12/14/1994		substation topology
Brazil	3/26/1996		Topology
US-West	7/2/1996	36 seconds	Several
US-West	7/3/1996	> 1 minute	Prevented by fast op. action
US-West	8/10/1996	> 6 minutes	Many
MAPP, NW Ontario	6/25/1998	>44 minutes	substation topology
San Francisco	12/8/1998	16 seconds	many
Brazil	3/11/1999	30 seconds	substation topology
Brazil	5/16/1999		Topology
India	1/2/2001		
Rome	6/26/2003		
US-NE	8/14/2003	> 1 hour	Many
Denmark/Sweden	9/23/2003	7 minutes	Many
Italy	9/28/2003	27 minutes	Many
Croatia	12/1/2003	few seconds	many
Greece	7/12/2004	14 minutes	few
Moscow/Russia	5/24-25/2005	14 hours	Many
European Blackout	11/4/2006	30 minutes	Many

Summary of blackout attributes

■ Impact:

- 3 of largest 4 blackouts occurred in last 10 years
- # of blackouts > 1000 MW doubles every 10 years

■ Pre-event conditions:

- Extreme weather
- Extreme conditions
- Weakened topology

■ Triggering events:

- Various kinds of N-1 or
- N-k ($k > 1$) with fault + nearby protection failure

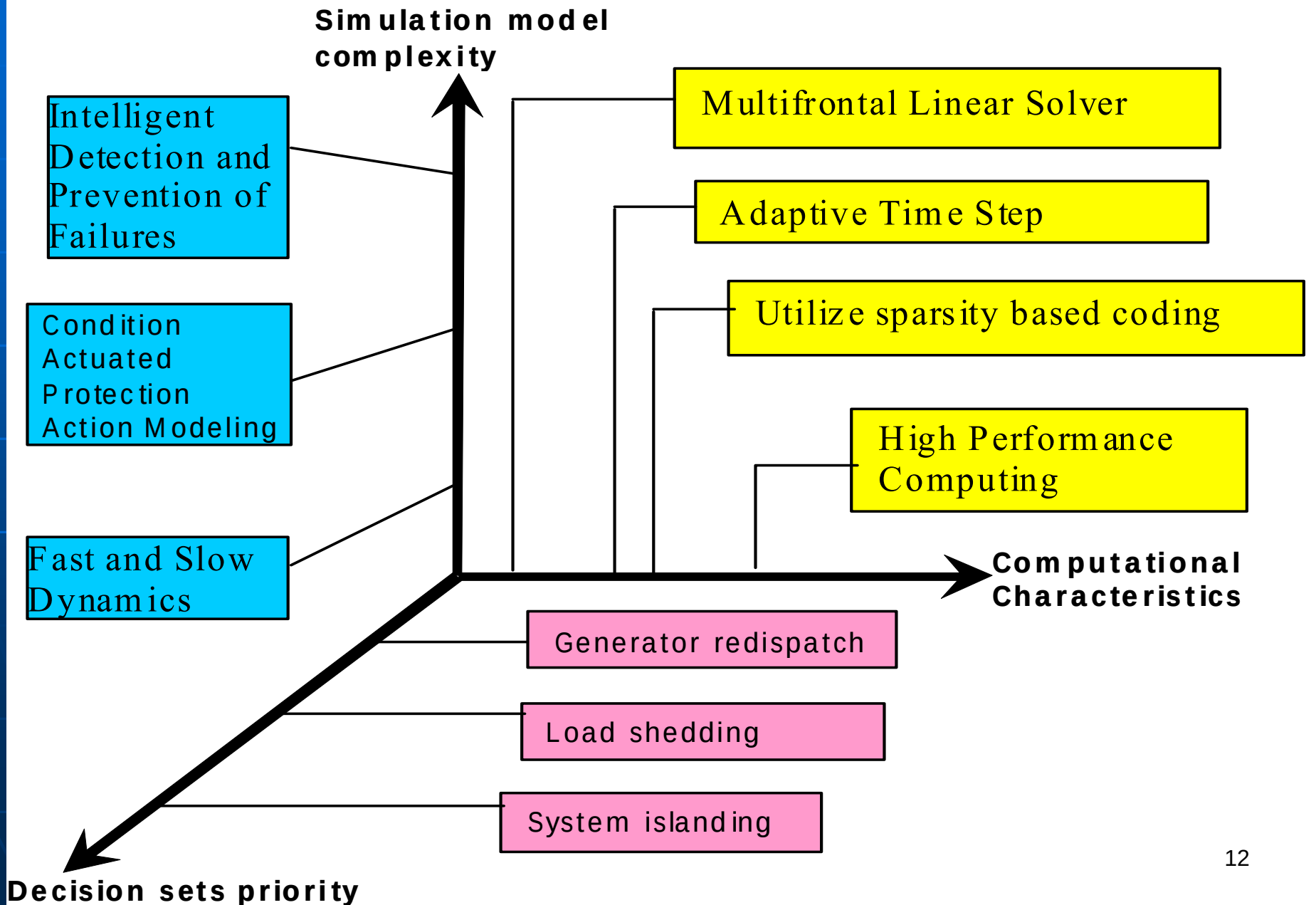
Summary of blackout attributes

- Pre-collapse events:
 - 50% involved generation, 95% involved transmission
 - 50% had significant time between initiating & pre-collapse events
 - 40% involved proper protection action
- Nature of collapse:
 - Successive tripping of components and/or
 - Voltage collapse
- Collapse time and # of events:
 - 50% were “slow”
 - 60% involved many cascaded (dependent) events

Scenario for 50% of blackouts

- 1. Weakened conditions: Heavy load, and/or one or more gen or ckt outage possibly followed by readjustments**
- 2. 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 go under-frequency and/or under-voltage.**
 - b. Components begin tripping quickly**
 - c. Uncontrolled islanding and/or voltage collapse**

Simulator Attributes



Initiating Contingency Selection

Terminology

Initiating event

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

N-k initiating events

- Implied that $k > 1 \rightarrow$ initiating events with loss of multiple elements
- N-1 events are order 1. N-k events may be order 1 to order k.

Successive events

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

Event-probability order and space

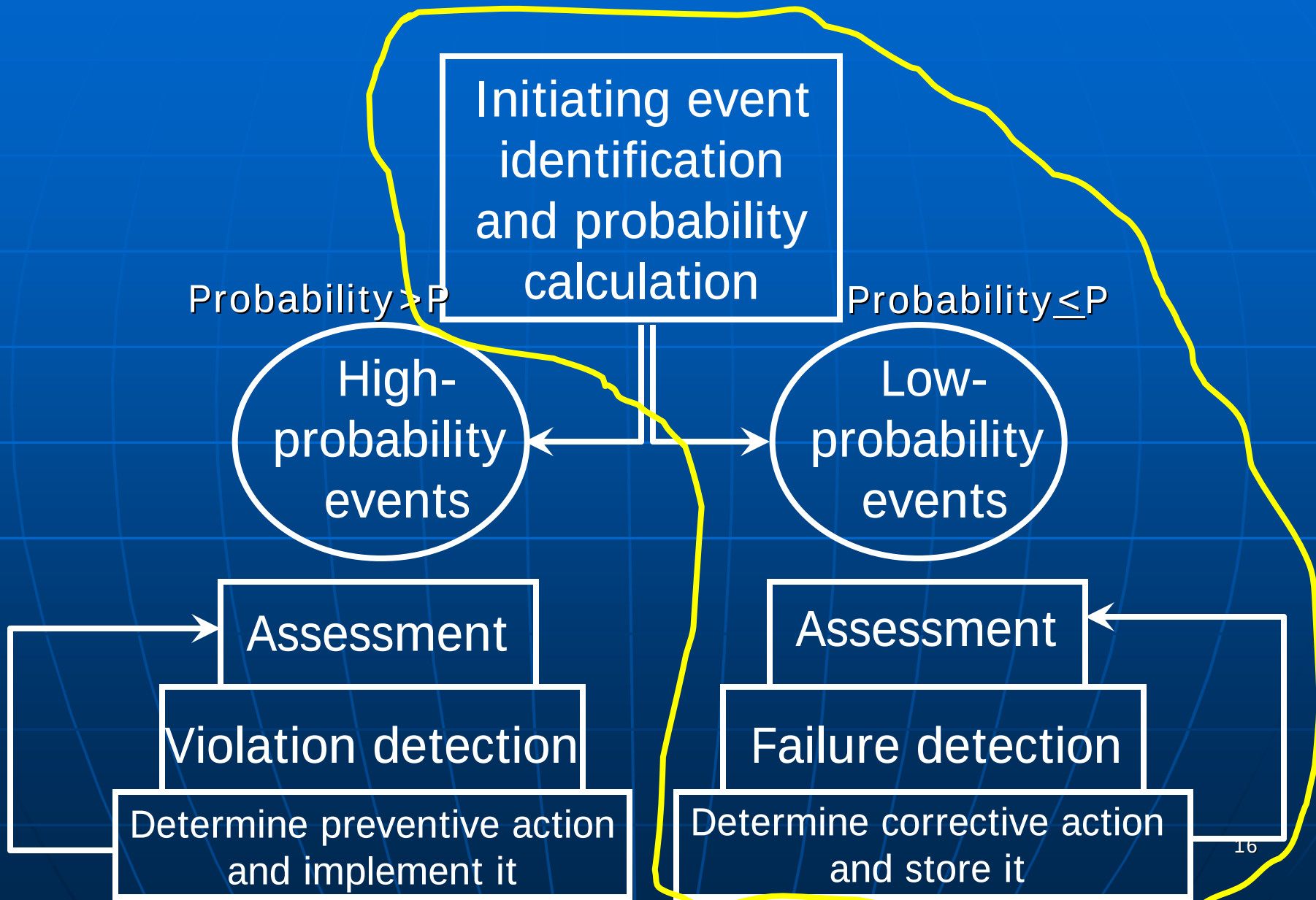
Probability order

- 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
- Probability space:
the space of all possible initiating events



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

Preventive/corrective action paradigm



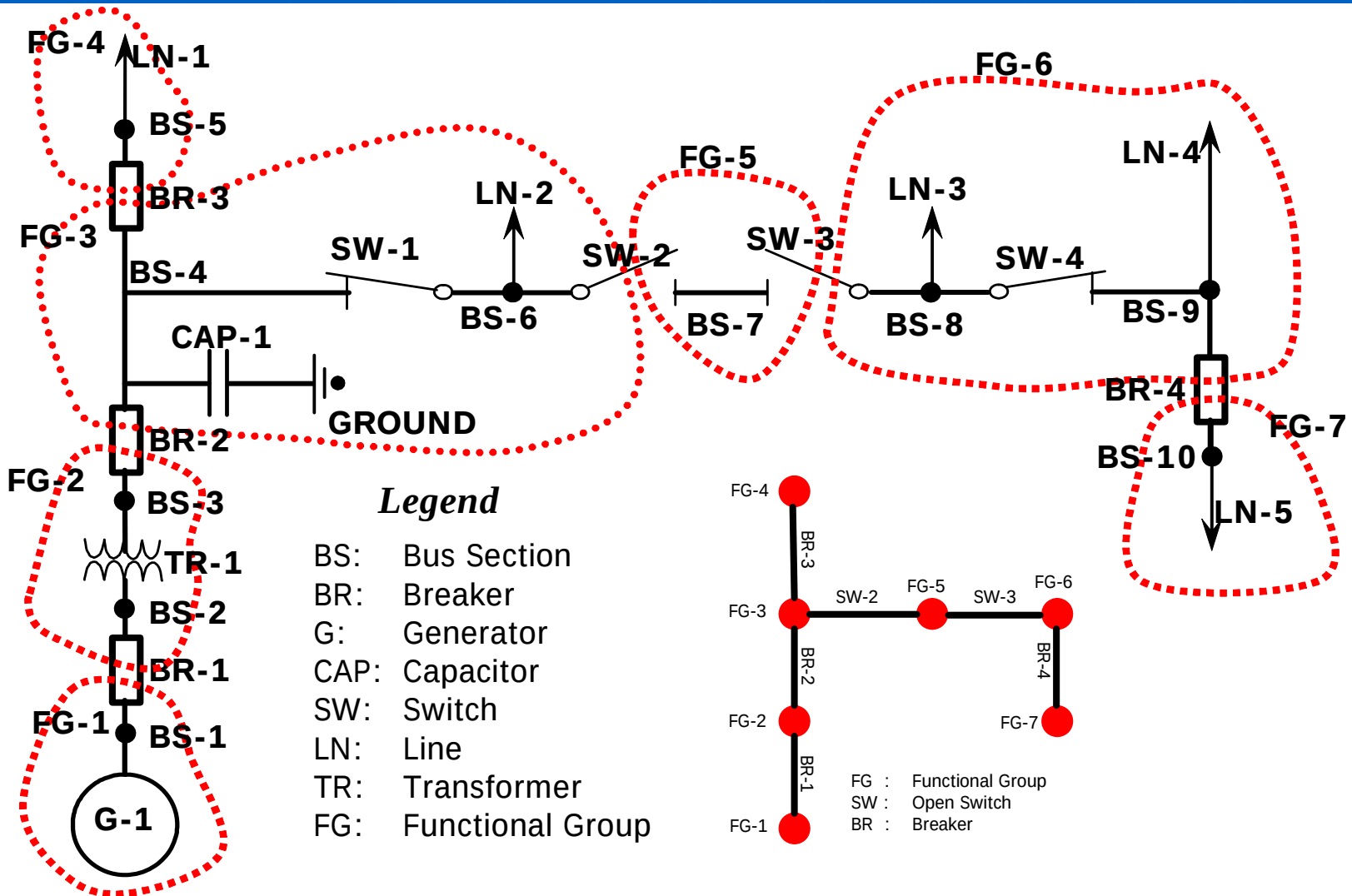
Component model

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 four 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. 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



High-Risk Initiating Events

Functional Groups provides for efficient initiating event identification and probability computation.

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

Functional Group Contingency

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

Stuck Breaker Contingency

$$P_{inadvertent}^{FG_j/FG_i} = \frac{\Pr(FG-j\ trips \cap FG-i\ trips)}{\Pr(FG-i\ trips)}$$

Inadvertent Tripping Contingency

Forms ~59% of the protection related category classification of major disturbances (Source: NERC's DWAG)

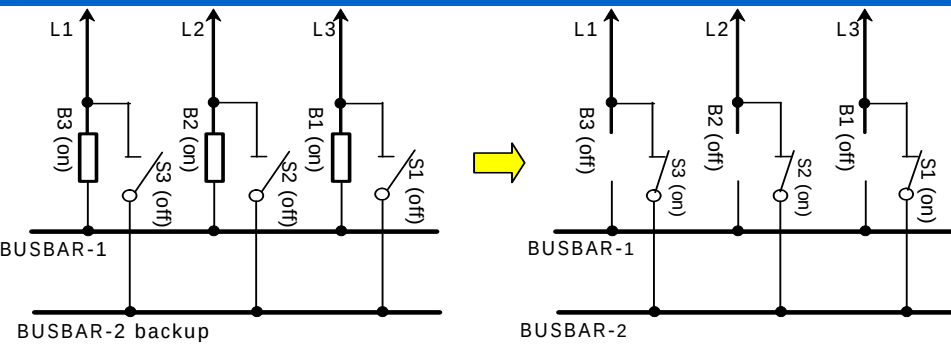
Topology Variation can lead to N-k outage

Variation in substation topology results from:

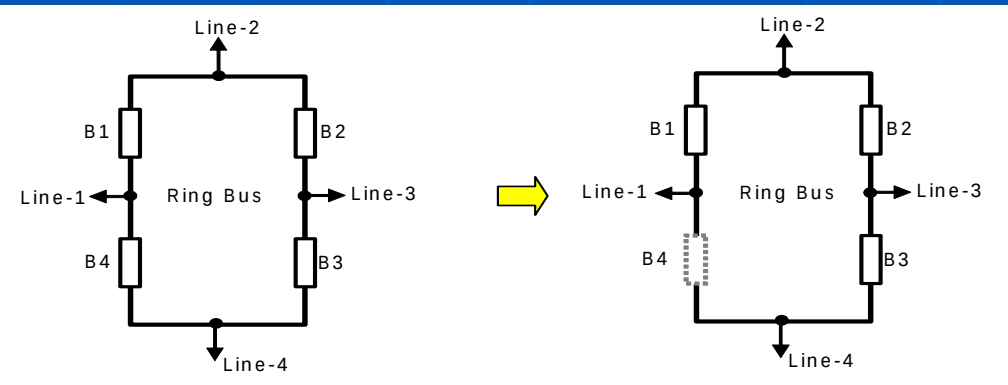
- Forced Outages &
- Operator action for
 1. Facility maintenance
 2. Mitigating undesirable operating condition as high circuit loading or out-of-limit voltages.

Change in system topology exposes the system to N-k contingency with probability order equivalent to N-1 contingencies and thus high risk.

Contingency Selection



N-3 exposure increases P^2 to $3P$ when maintaining busbar 1 in double breaker-double bus, for fault on any line. An N-1 or N-2 contingency cannot occur.



N-2 exposure increases P^2 to P when maintaining B4 in ring bus, for fault on Line 3. An N-1 contingency for Line 3 cannot occur.

Configuration	Stuck Breaker probability	Probability of ITC
Ring Bus	$P_{FSB} = D \times B \times P_{FG}$ $= p_{sb} \times \begin{pmatrix} 2p_l \\ 2p_l \\ 2p_l \\ 2p_l \end{pmatrix}$	$\begin{pmatrix} P_{FG_1}^{ITC} \\ P_{FG_2}^{ITC} \\ P_{FG_3}^{ITC} \\ P_{FG_4}^{ITC} \end{pmatrix} = \begin{pmatrix} \dots \\ \dots \\ [P(FG_2 \cap FG_3) + P(FG_3 \cap FG_4)] \left(1 / P_{FG_3}^{FT} \right) \\ \dots \end{pmatrix}$

Test Results on IEEE RTS 96 Test System

Number of contingencies of type N-k resulting from a single fault (Order P) for IEEE RTS96

k	1	2
No.	63	4

Number of contingencies of type N-k resulting from a fault/breaker failure (order P²) for IEEE RTS96

k	1	2	3	4
No.	82	88	1	3

Number of contingencies of type N-k resulting from ITC (Order P²) for IEEE RTS96

k	2	3	4
No.	137	5	5

Testing on Large EMS Model

Use graph-search to identify functional groups, and order P and P^2 contingencies

Number of components in the system					
Type	Bus	Line	Xfmr	Gen	Shunt
No.	1549	1830	697	353	357

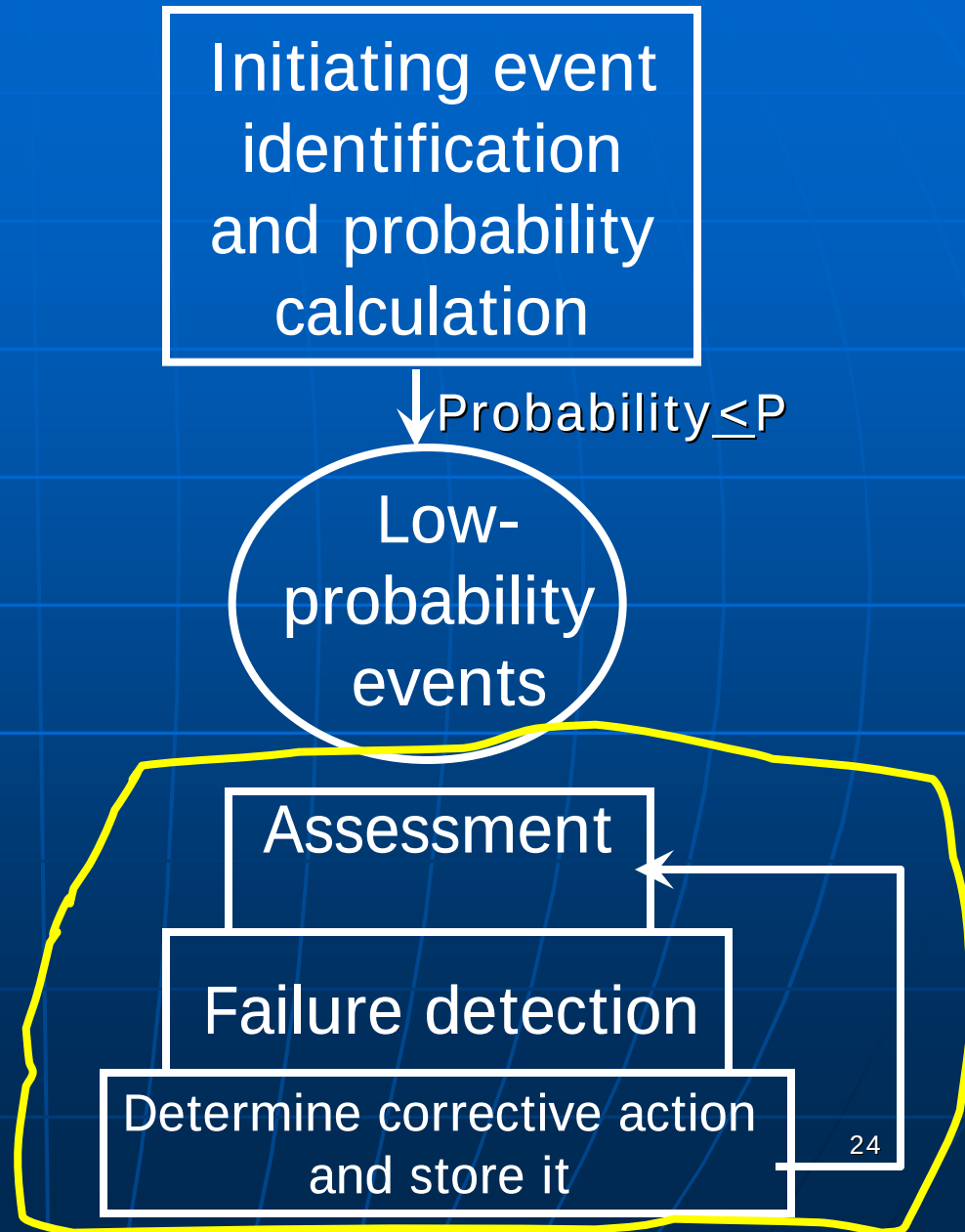
Number of contingencies of type N-k resulting from a single fault (Order P)

k	1	2	3	4	5	6	7	8	9	10	11
No.	2022	468	49	14	5	3	2	1	0	0	1

Number of contingencies of type N-k resulting from a fault/breaker failure (order P^2)

k	1	2	3	4	5	6	7	9	10	11	12	13	14	15	17
No.	3011	1248	356	134	63	31	23	0	1	1	7	1	0	0	1

Assessment, detection, & corrective action determination



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

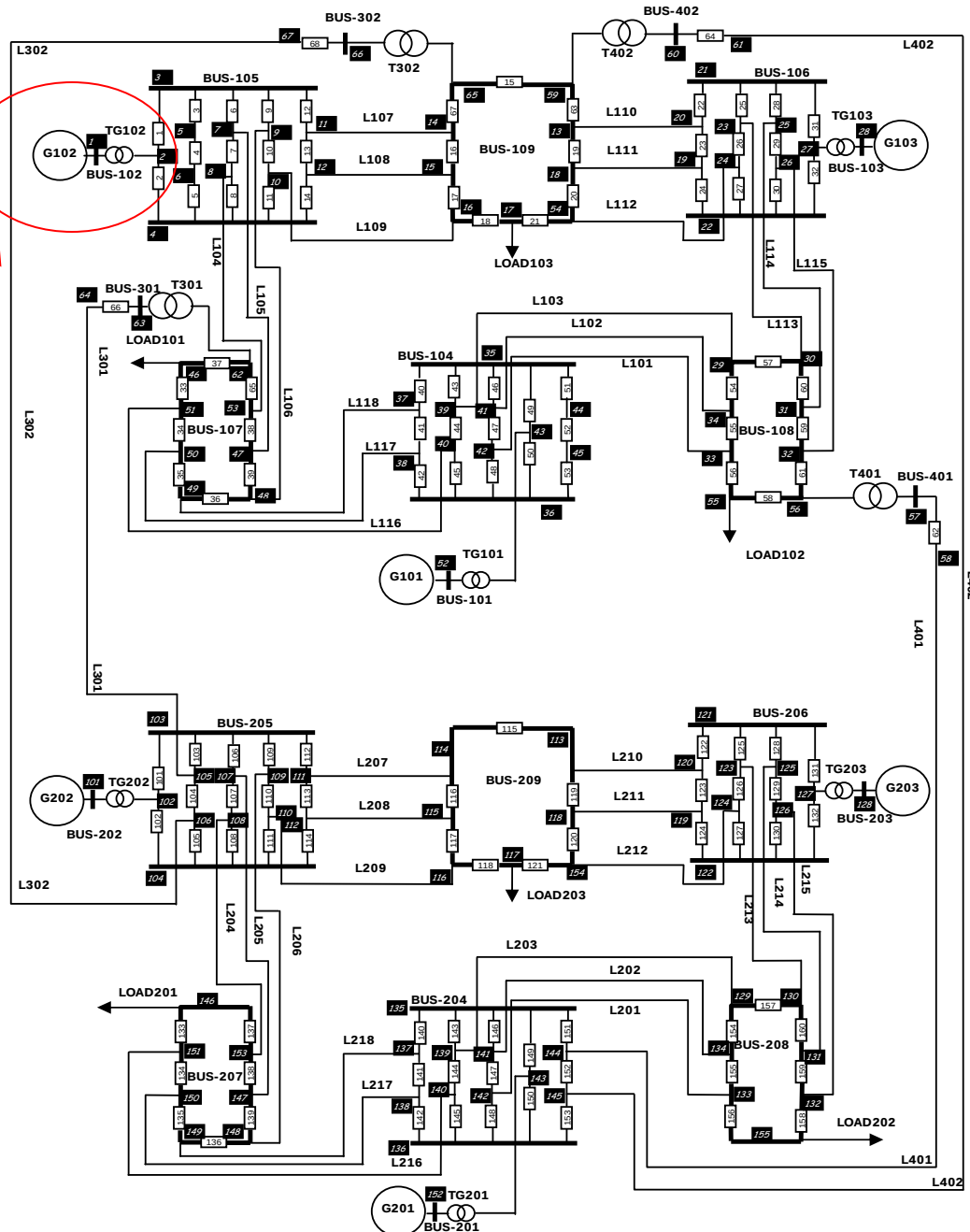
■ Failure prevention:

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

ONE-LINE DIAGRAM OF THE TEST SYSTEM

Load ramping 20%
from $t=900s$ to
 $t=2700s$

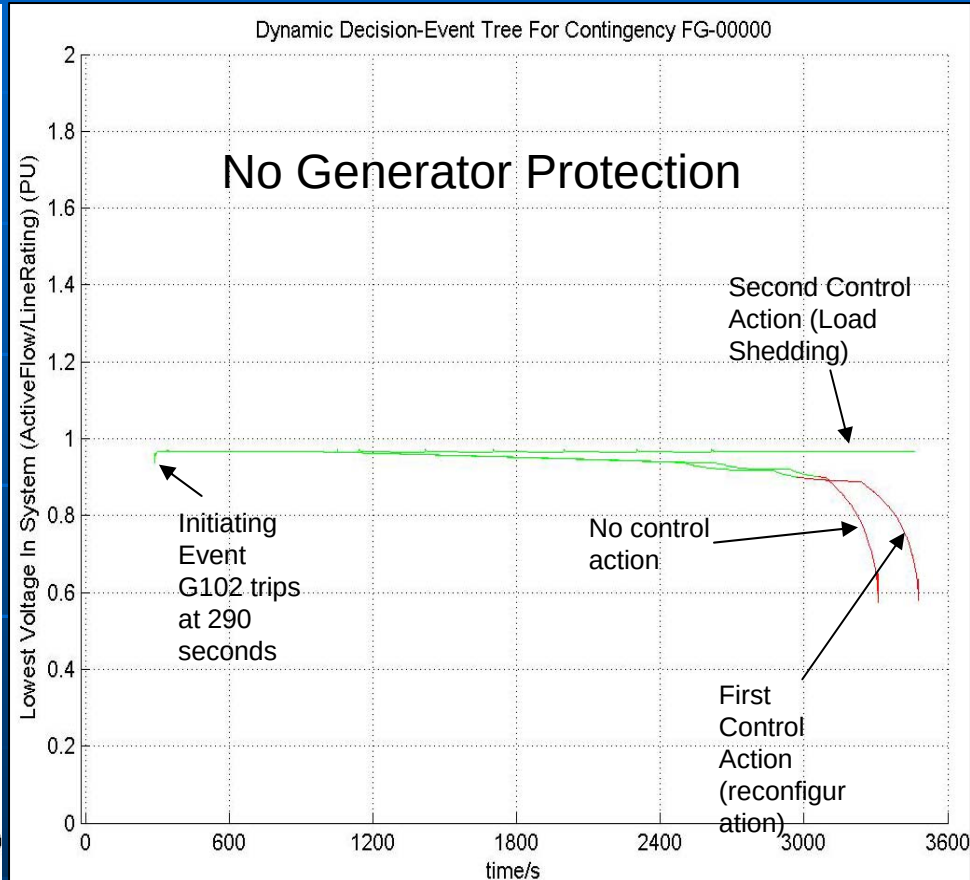
G102 (initiating
generator
trip at $t=290s$)



Tracking and Avoidance Decision Support Tool



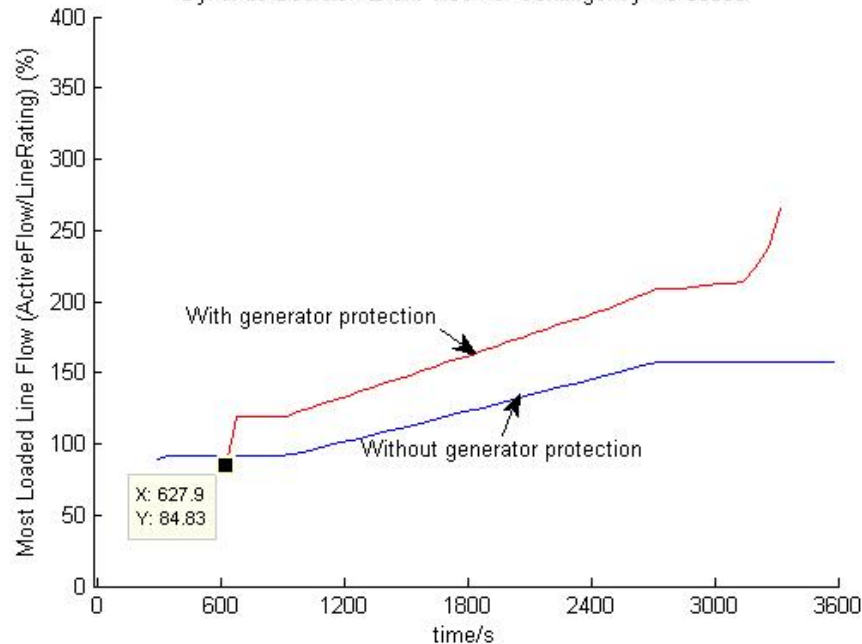
Circuit loading



Voltage response of system

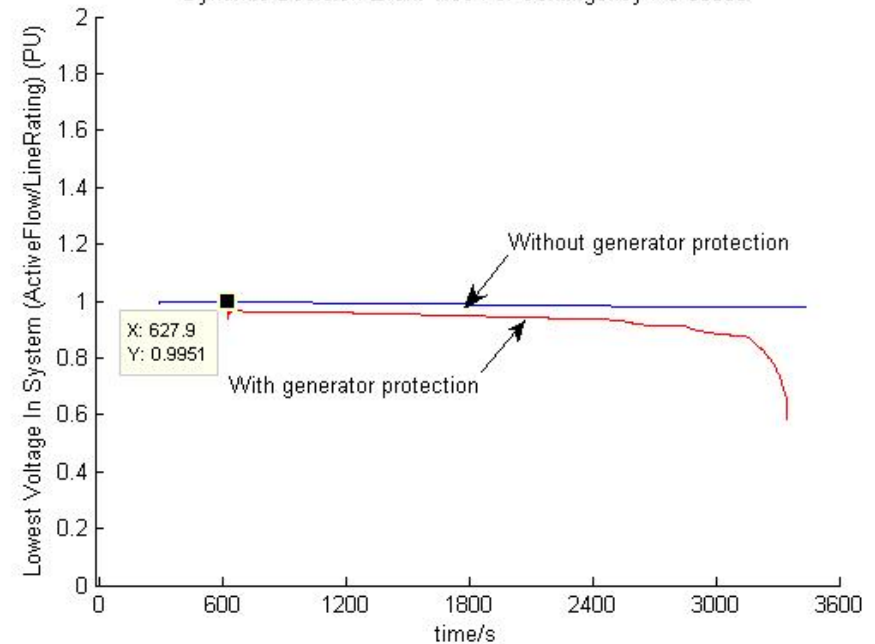
With and Without Generator Protection

Dynamic Decision-Event Tree For Contingency FG-00000



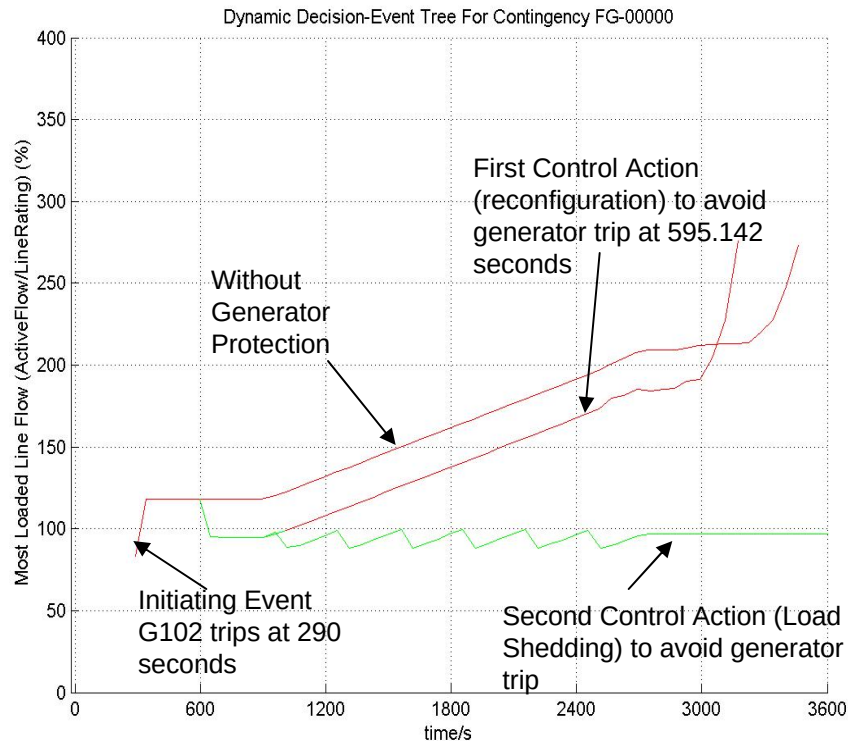
Circuit loading with and without generator protection

Dynamic Decision-Event Tree For Contingency FG-00000

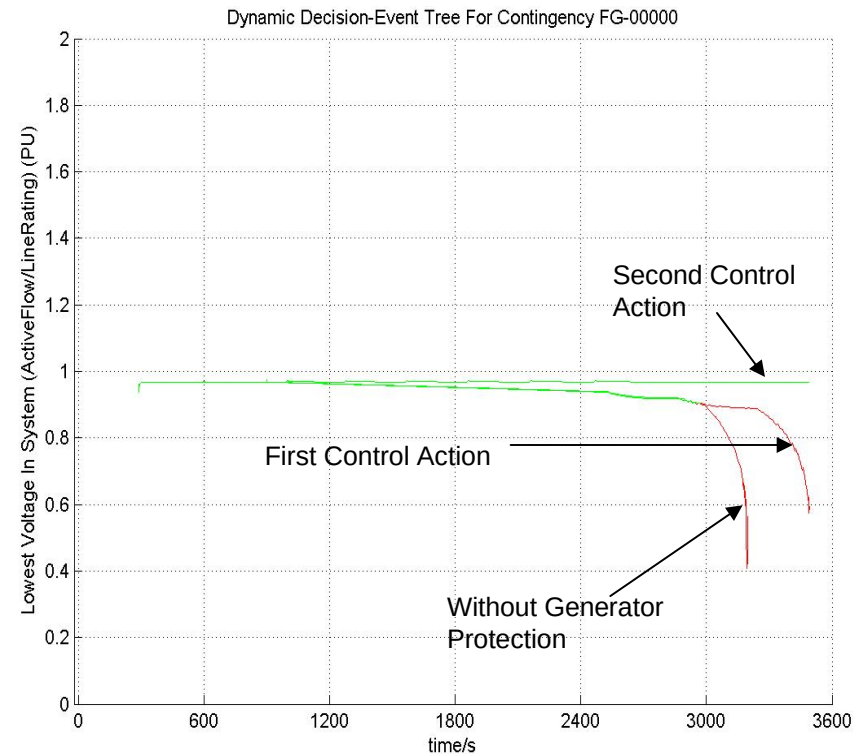


Voltage response of system with and without generator protection

Predicting Response and Identifying Control Actions



Circuit loading with and without generator protection



Voltage response of system with and without generator protection

**Load ramping 20 %
from $t=900\text{s}$ to
 $t=2700\text{s}$**

A Cascading Scenario

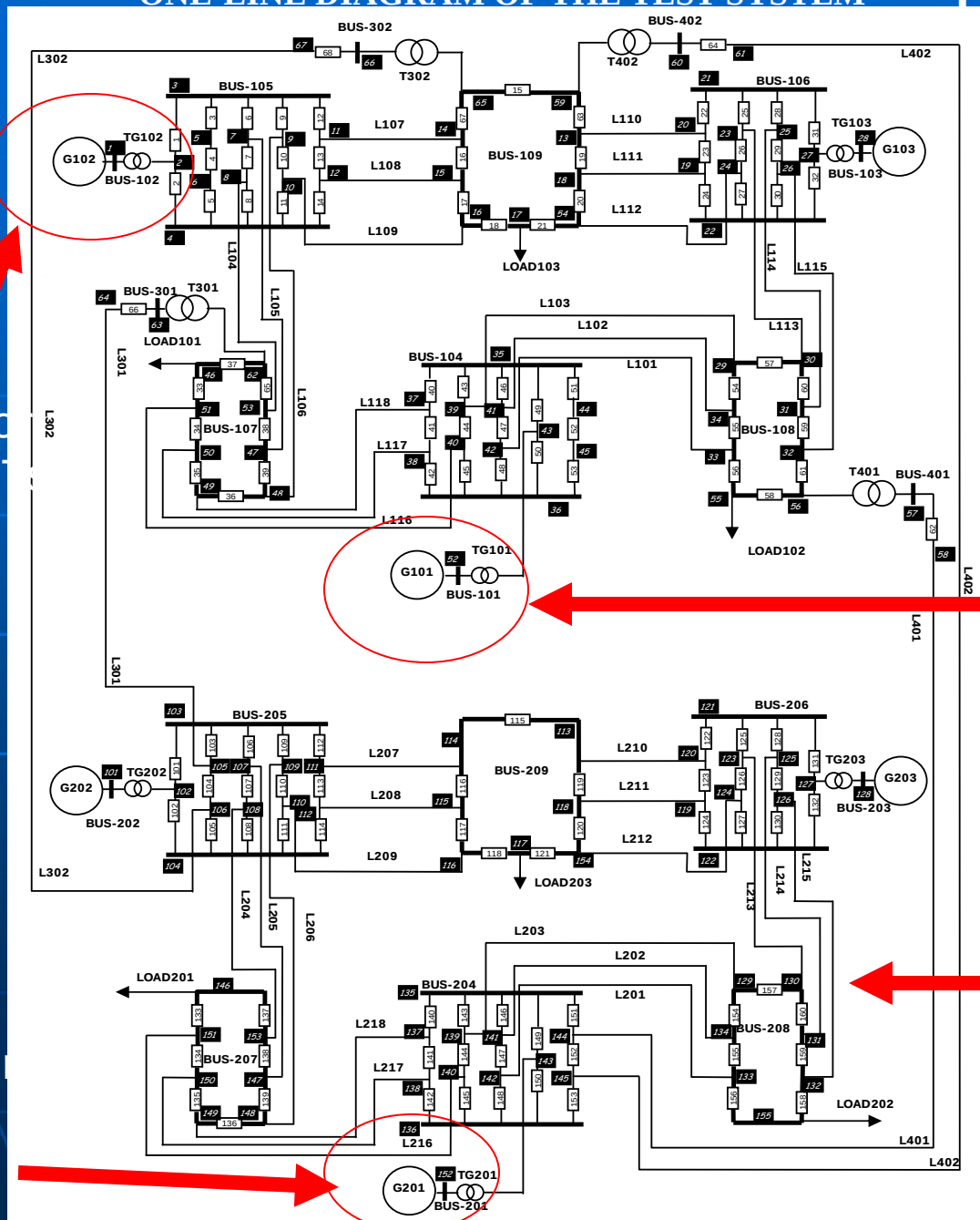
G102 (generated
trip at $t=925.3$

Generator trip initiated by overexcitation (V/Hz relay)

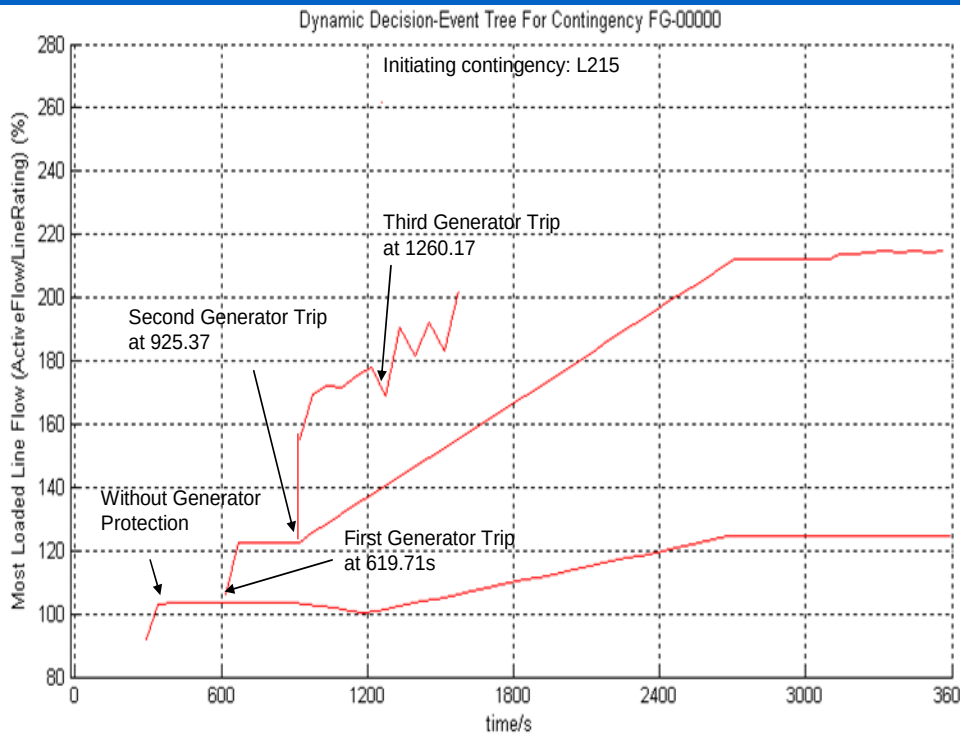
G101 (generator trip at $t=619.71s$)

G201 (generator trip at $t=1260.17\text{s}$)

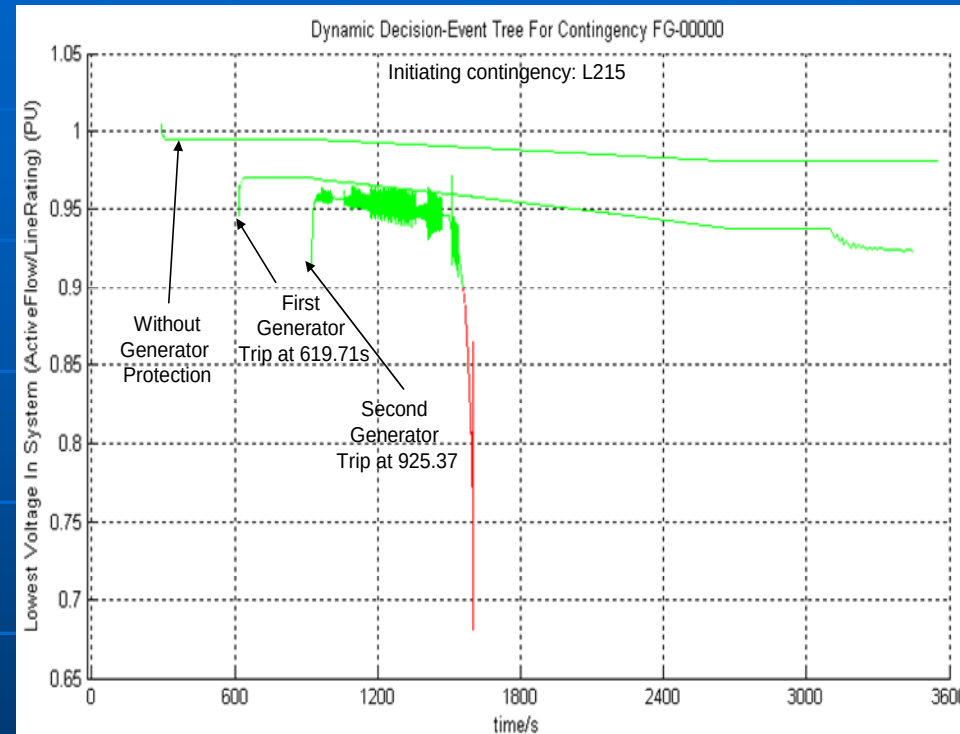
- L215 (initiating event at $t=300s$)



A Cascading Scenario



Circuit loading with and without generator protection



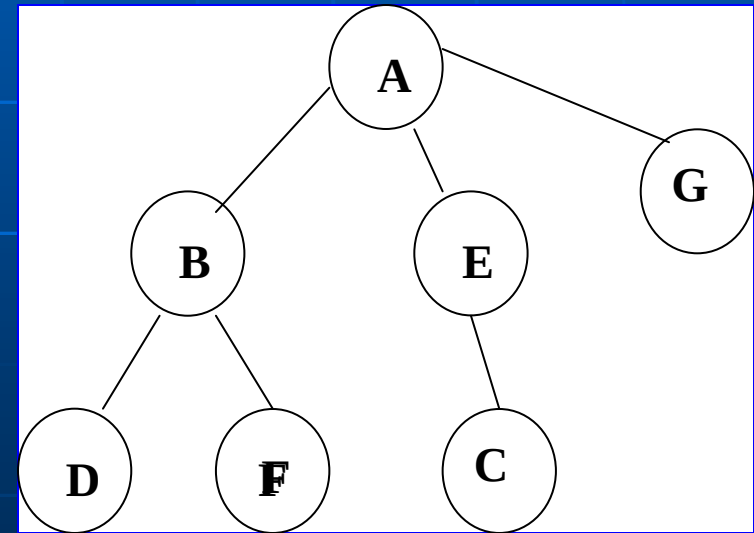
Voltage response of system with and without generator protection

Automatic Island Detection and Simulation

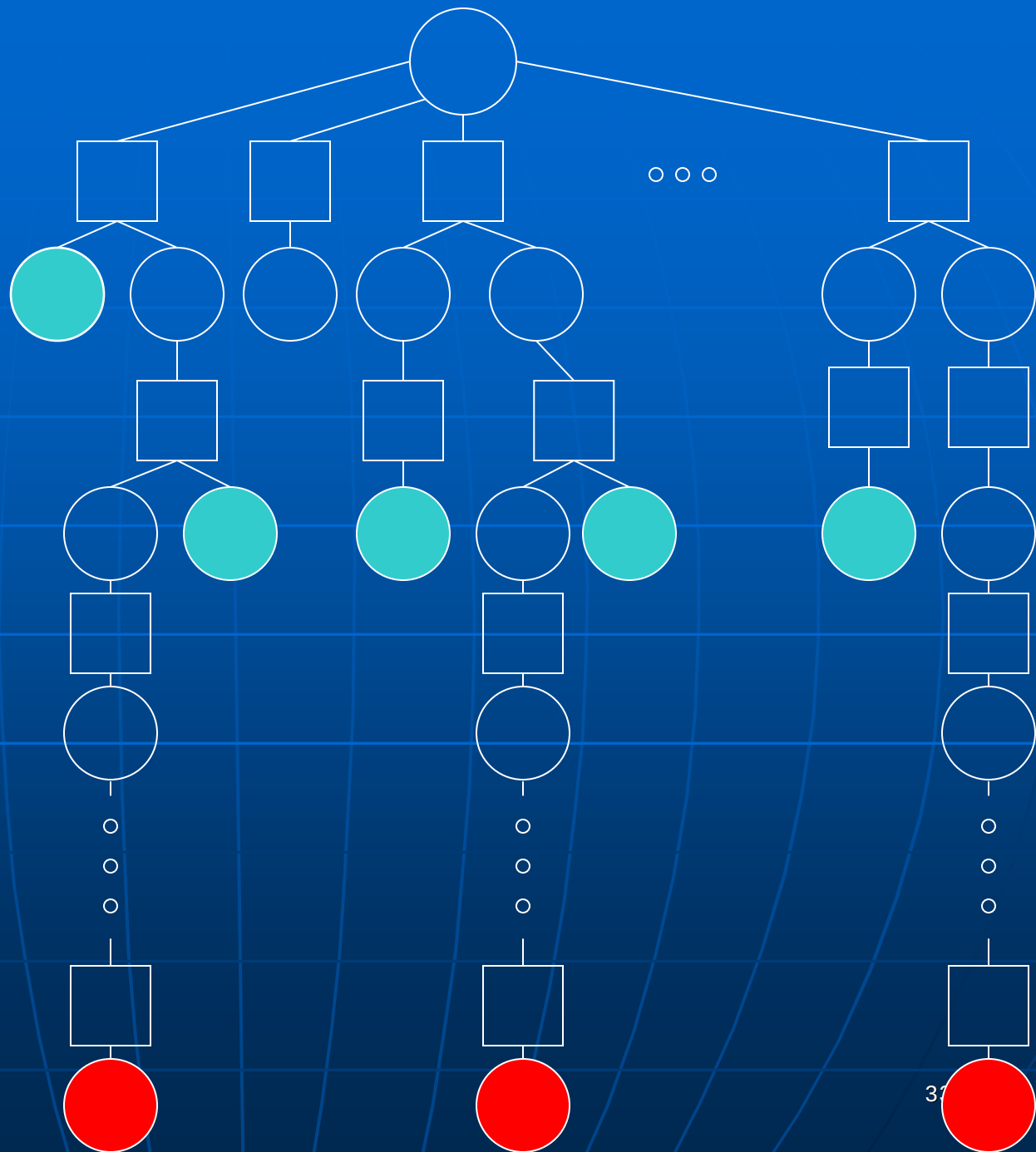
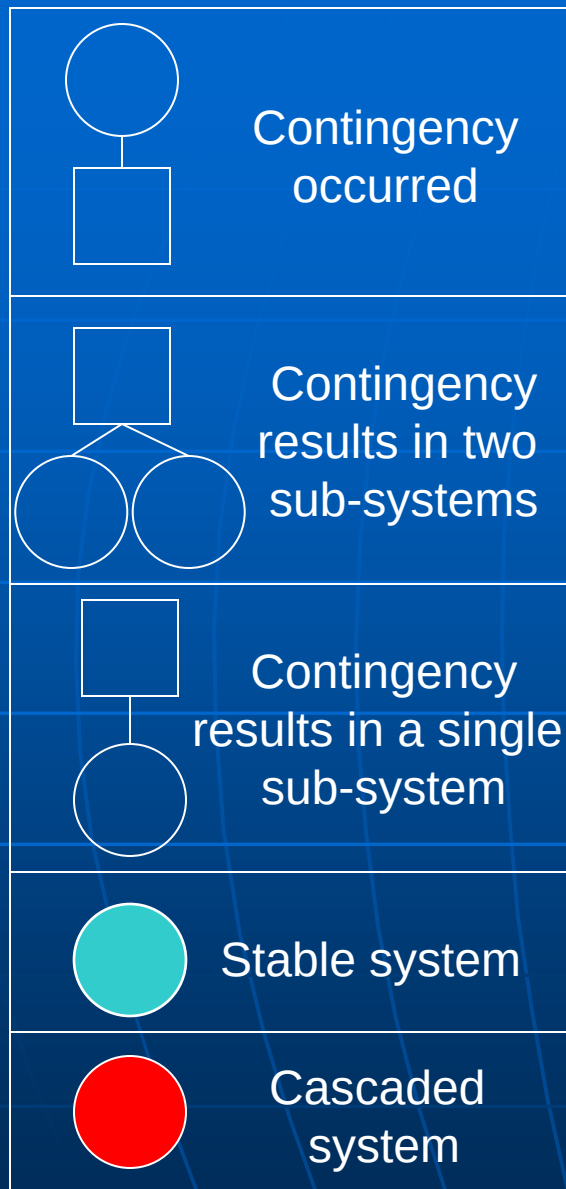
- Depth First Search (Recursive Algorithm)
- Graph Search Algorithm for component detection within each Island

• The figure shown is a representative structure of the cascading phenomena starting at root node A and progressing on any of the three branches initially, which can further branch depending on the trajectory of the system.

• DFS is ideally suited for simulating the cascading phenomena in power system.

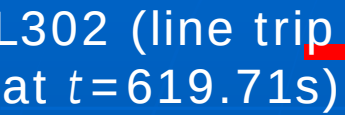


Traversing order: A, B, D, F, E, C, G



Note: Contingencies at first level are deliberate

**Load ramping 20 %
from $t=900\text{s}$ to
 $t=2700\text{s}$**



L301 (line trip
at $t=619.71\text{s}$)

G101
(generator trip
at $t=619.71\text{s}$)

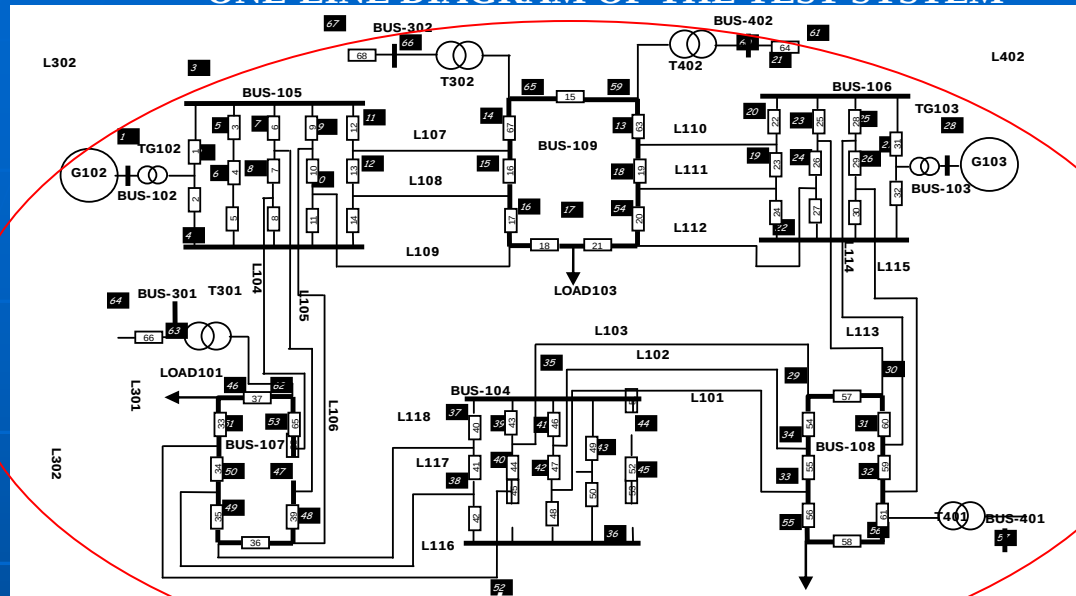
L402 (line trip
at $t=619.71\text{s}$)

L401 (line trip
at $t=619.71\text{s}$)

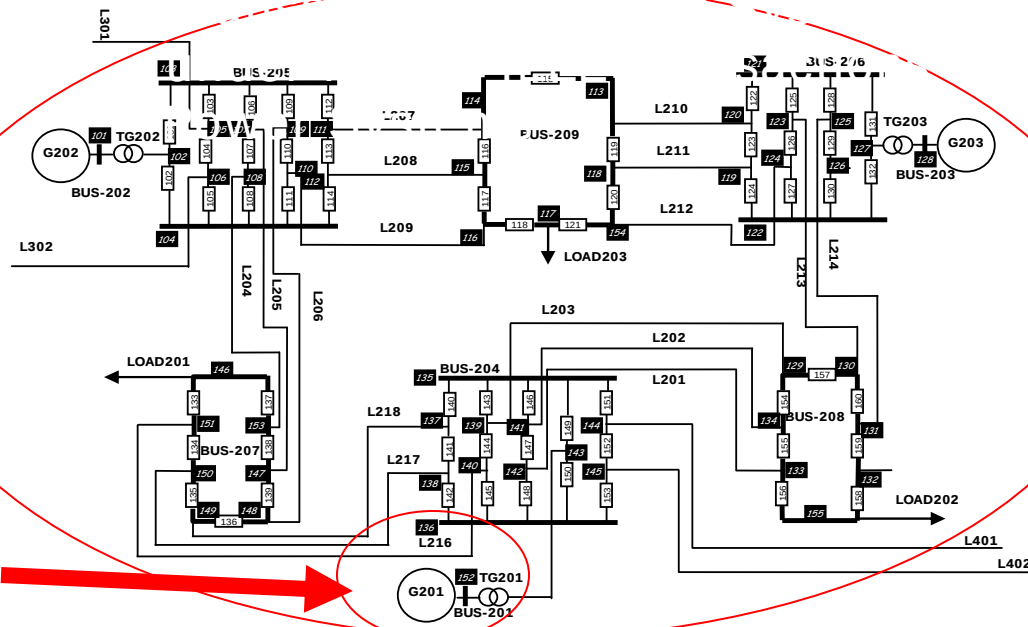
L215 (initiating event at $t=300s$)

ONE-LINE DIAGRAM OF THE TEST SYSTEM

Load ramping 20 %
from $t=900s$ to
 $t=2700s$

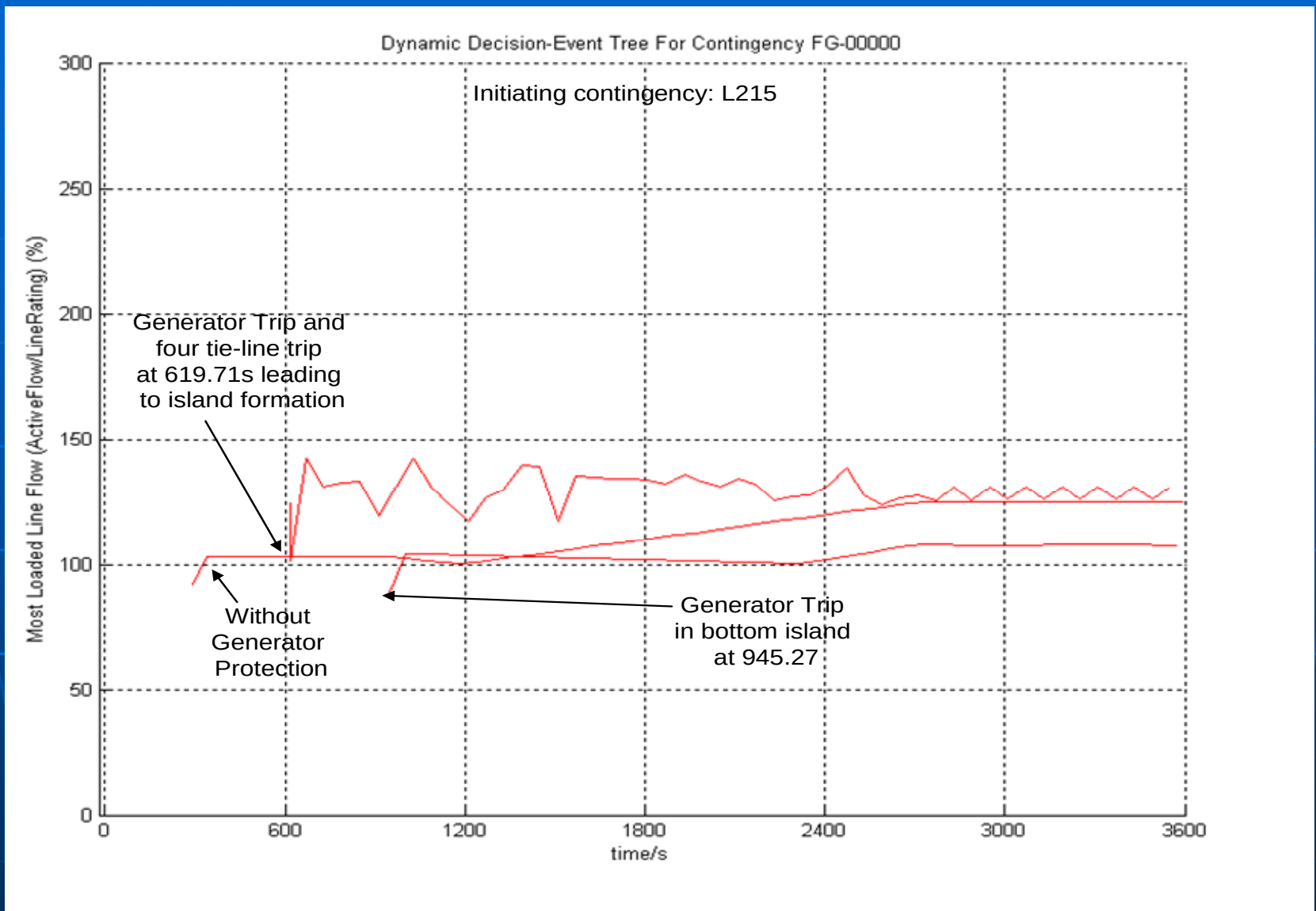


Top
Island



Bottom
Island

G201
(generator
trip at
 $t=945.27s$)



Circuit loading with and
without generator protection

Numerical Methods

Integration algorithm

The power system dynamic equations can be summarized as

$$\frac{dx}{dt} = f(x, y)$$

$$0 = g(x, y)$$

which, are discretized using Theta-method giving

$$[x_{n+1} - x_n - h\theta\dot{x}_n] - (1-\theta)hf(x_{n+1}, y_{n+1}) = 0$$

$$g(x_{n+1}, y_{n+1}) = 0$$

which is summarized as a set of non-linear equations given by:

$$F(x_{n+1}, y_{n+1}) = 0$$

which are solved at each time step using Newton-Raphson method:

$$x_{n+1}^{(i)} = x_{n+1}^{i-1} - \gamma\Delta x$$

$$y_{n+1}^{(i)} = y_{n+1}^{i-1} - \gamma\Delta y$$

where Δx and Δy are solved as:

$$J \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \begin{bmatrix} R_x \\ R_y \end{bmatrix}$$

equivalent to a linear system:

$$Ax = b$$

Computational speed is the major goal...

- Intelligent Jacobian Building
- Variable Time Step
- Choice of Integration Algorithm
- Very fast Sparse Linear Solvers
 - Direct Methods
 - Intelligent Symbolic and Numeric Factorization
 - Iterative Methods
 - Development of robust preconditioner
- Parallelization

Ingredients in the solution of sparse linear systems

Ordering step:

Reorders rows and columns to reduce fill in L & U .

Symbolic factorization step:

Determine locations of nonzeros in L & U .

Set up data structures for storing nonzeros of L & U .

Allocate memory for the nonzeros.

Numerical factorization step:

Input numerical values.

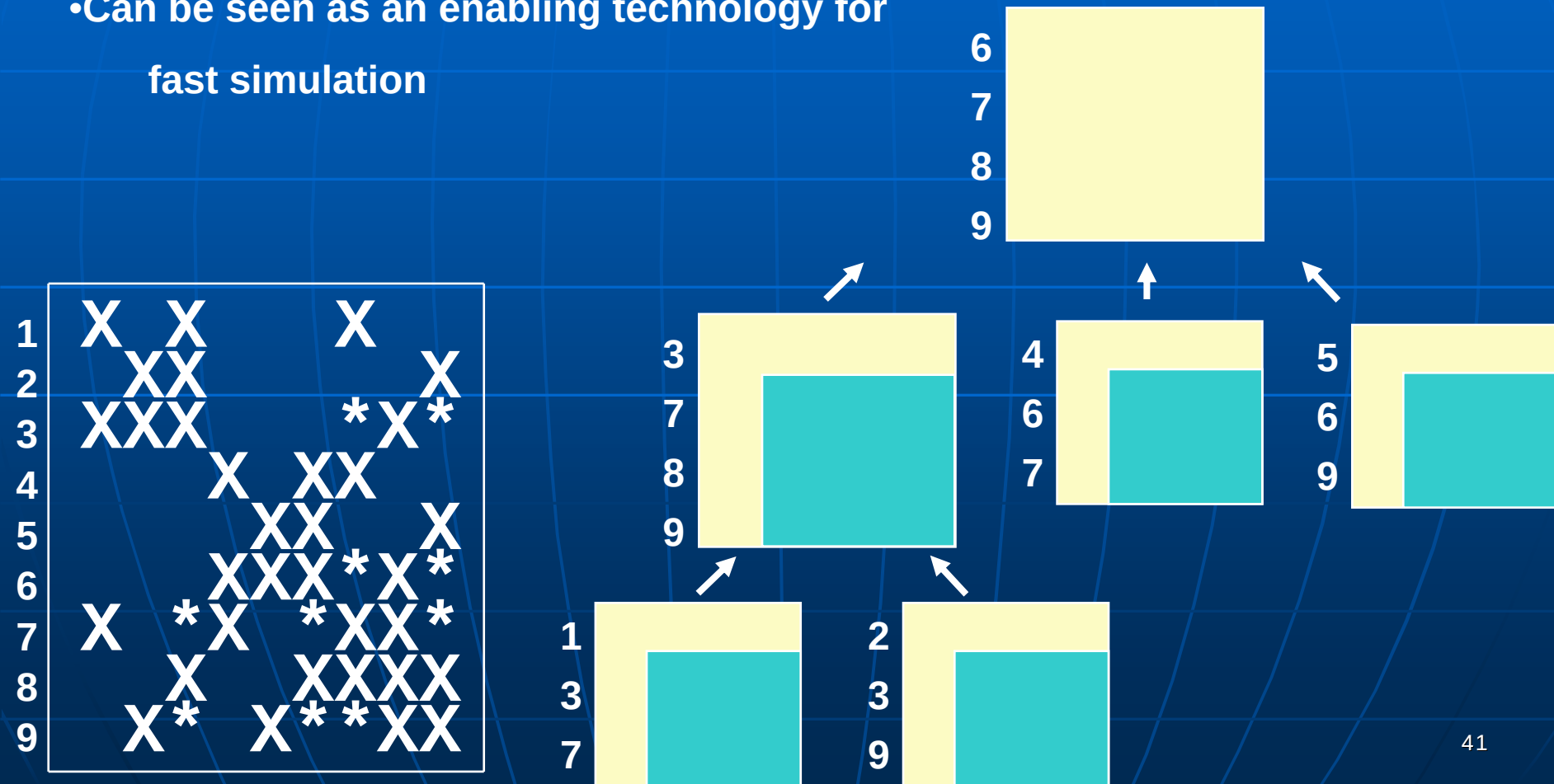
Compute L & U via intelligent factorization on multiple small, but dense “fronts”, with pivoting to maintain numerical stability.

Triangular solution step:

Use L & U to perform forward and backward substitutions to solve linear system.

Multifrontal Methods for Linear Solvers

- Not in open literature for power system time domain simulation applications
- Not Used in Commercial Grade Simulators
- Can be seen as an enabling technology for fast simulation

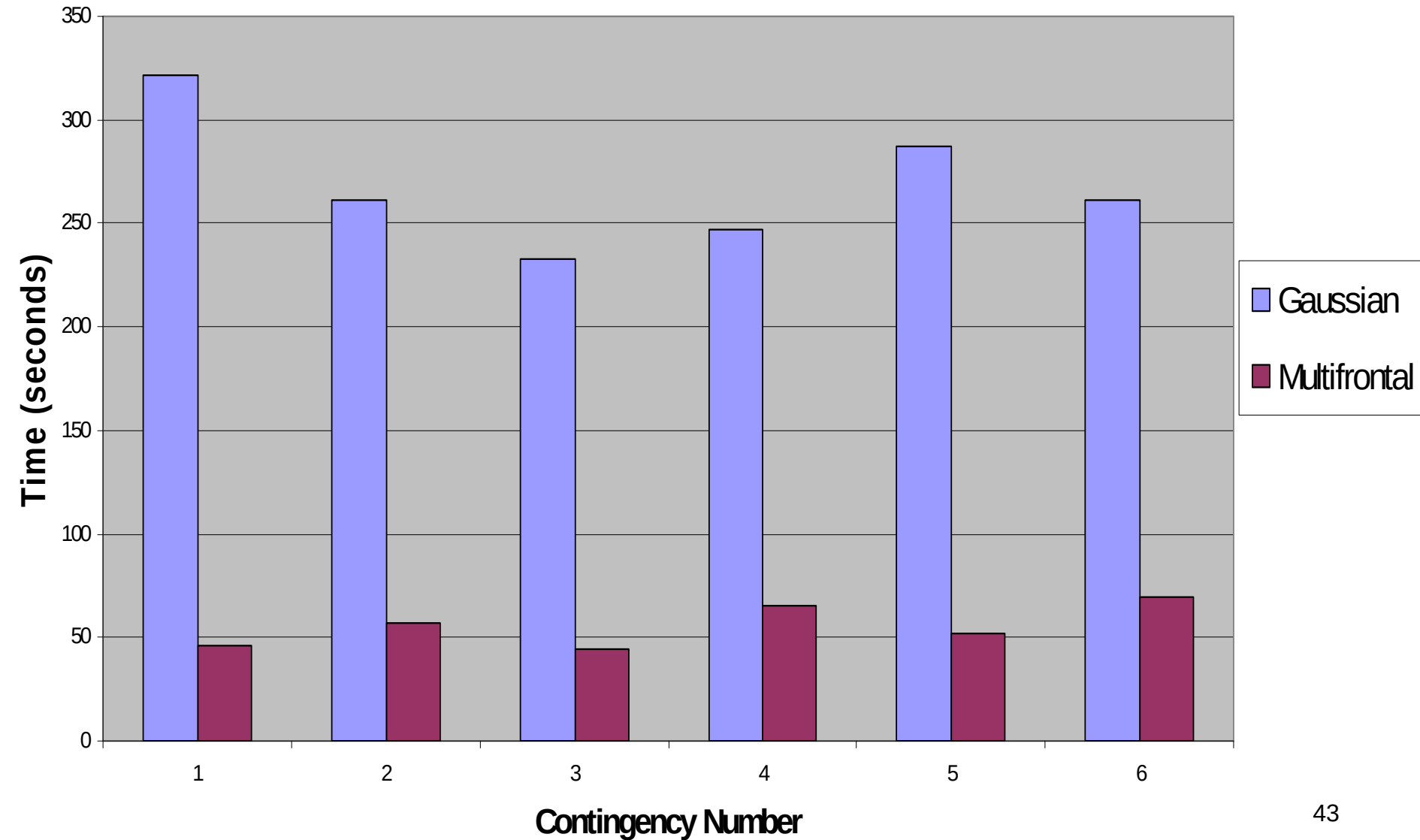


Multifrontal factorization

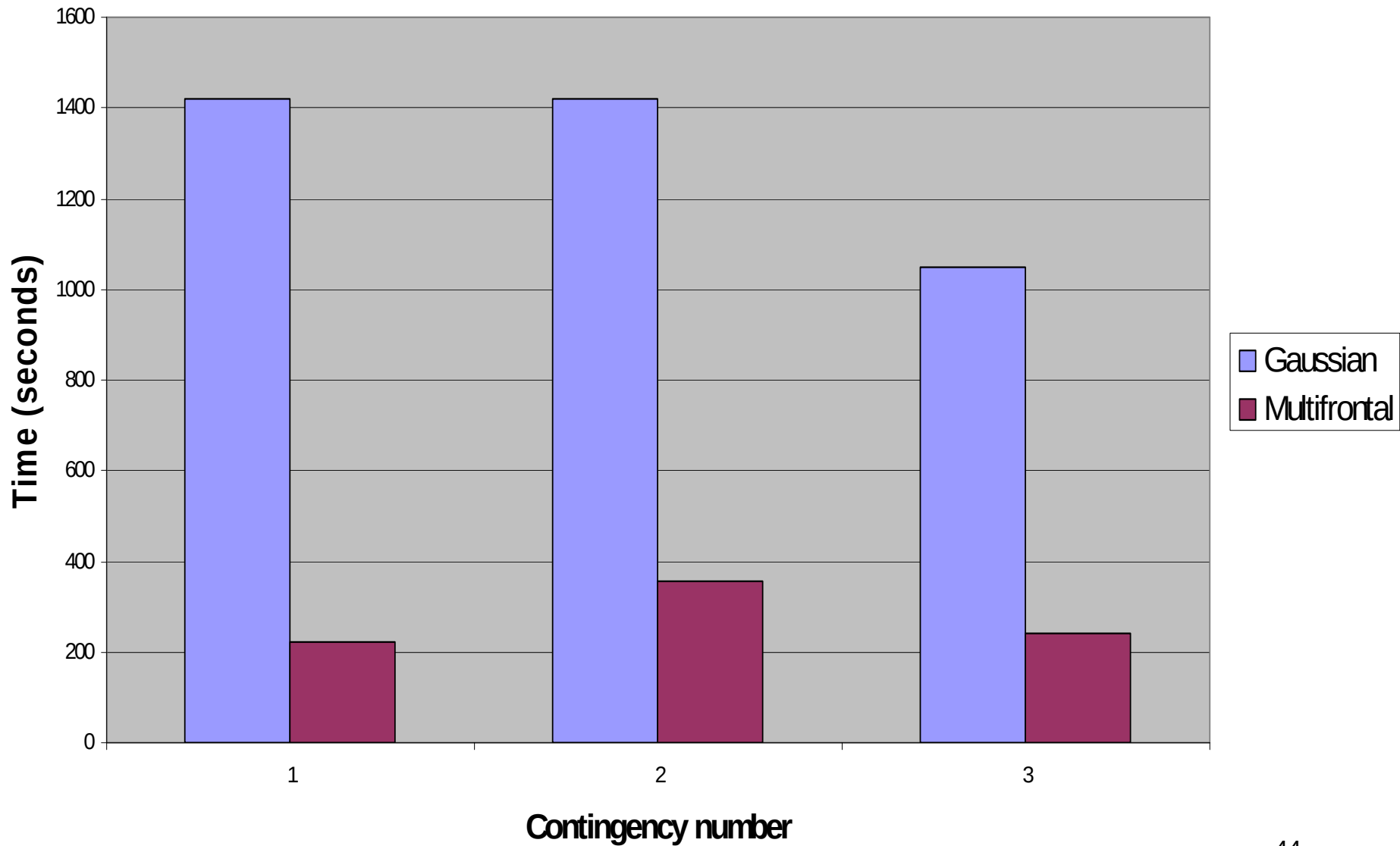
- All arithmetic happens on dense square or rectangular matrices.
- Needs extra memory for a stack of pending update matrices
- Potential parallelism:
 1. between independent tree branches
 2. parallel dense ops on frontal matrix

Code	Technique	Scope	Contact
MA41	Multifrontal	Sym-pat	HSL
MA42	Frontal	Unsym	HSL
MA48	Right-looking	Unsym	HSL
MA57	Multifrontal	Sym	HSL
MA67		$\begin{pmatrix} H & A^T \\ A & 0 \end{pmatrix}, H = H^T$	HSL
SPARSE	Right-looking	Unsym	Kundert
SPARSPAK	Left-looking	SPD	George
SPOOLES	Left-looking	Sym and Sym-pat	Ashcraft
SuperLLT	Left-looking	SPD	Ng
SuperLU	Left-looking	Unsym	Li
UMFPACK	Multifrontal	Unsym	Davis

Performance Comparison for a 6 bus Test System



Performance Comparison for a 32-generator IEEE Test System



Summary

1. Probability-based contingency selection, using substation topology breaker-switch data, is a must for today's EMS. No reason not to.
2. Continuous, anticipatory computing to provide decision-support corrective action for lower-probability events makes sense.
 - Preparing operators for rare events is fundamental to operating engineering systems having catastrophic potential; has precedent in air traffic control, nuclear, & process control.
 - It motivates significant improvements in modeling and computation. Multifrontal solvers for linear systems should be widely implemented in EMS software.

Publications

1. Multifrontal Solver for Online Power System Time Domain Simulation: under review IEEE Transactions on Power Systems
2. Probability Estimation of High Risk N-k Inadvertent Contingencies for Online Security Assessment: under review IEEE Transactions on Power Systems
3. DFS based algorithm for simulating cascading: under preparation
4. Time Domain simulator with Generation Protection: under preparation
5. A study of Blackouts in past 40 years: under preparation