Operational Defense of Power System Cascading Outages

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Cascading Failures & Blackouts
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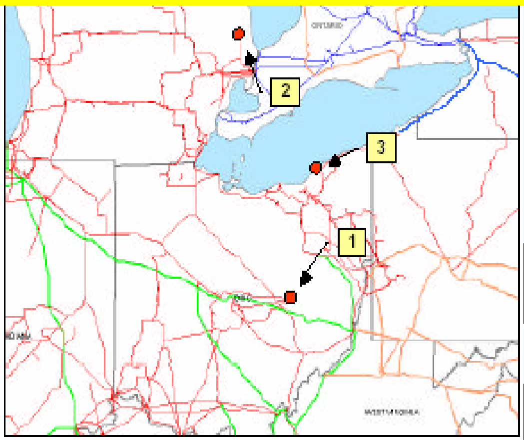
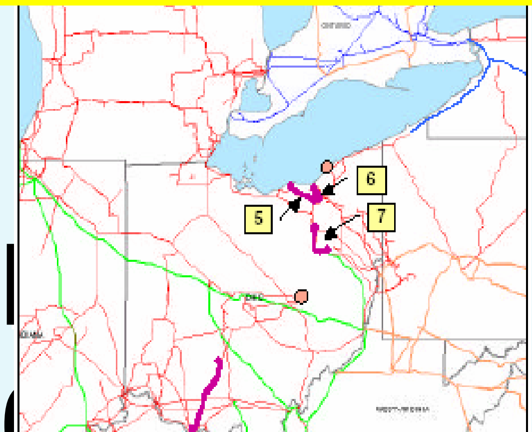
Overview

1. Review of Aug 14, 2003
2. Summary of previous blackouts
3. Blackout attributes
4. Approaches to reduce frequency/severity of high consequence events
5. Emergency Response System
6. Triggering events
7. Simulator attributes
8. Final comments

1. 12:05	Conesville Unit 5, 375 MW	Weakening conditions
2. 1:14	Greenwood Unit 1, 785 MW	
3. 1:31	Eastlake Unit 5, 597 MW, overexcitation	
4. 2:02	Stuart – Atlanta 345 kV (brush fire)	Triggering event
5. 3:05	Harding-Chamberlain 345 kV (tree)	SLOW PROGRESSION
6. 3:32	Hanna-Juniper 345 kV (tree)	
7. 3:41	Star-South Canton 345 kV (tree)	
8. 3:39-4:05	16 138 KV lines around Akron tripped	
9. 4:05	Sammis-Star 345 kV (zone 3)	





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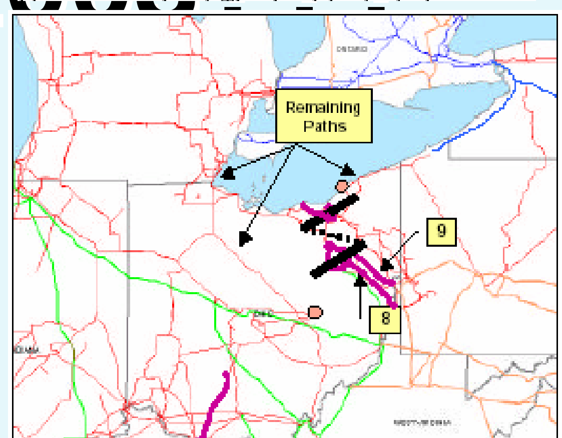

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9. 4:05	Sammis-Star 345 kV (zone 3, tree)	
10. 4:08:58	Galion-Ohio Central-Muskingum 345 kV (zone 3)	
11. 4:09:06	East Lima-Fostoria Central 345 kV (zone 3)	
12. 4:09:23-4:10:27	Kinder Morgan (rating: 500 MW; loaded to 200 MW)	
13. 4:10	Harding-Fox 345 kV	
14. 4:10:04 – 4:10:45	20 generators along Lake Erie in north Ohio, 2174 MW	
15. 4:10:37	West-East Michigan 345 Kv (zone 3)	FAST PROGRESSION (cascade)
16. 4:10:38	Midland Cogeneration Venture, 1265 MW (redu	
17. 4:10:38	Transmission system separates northwest of De	
18. 4:10:38	Perry-Ashtabula-Erie West 345 kV (zone 3)	
19. 4:10:40 – 4:10:44	4 lines disconnect between Pennsylvania & New York	
20. 4:10:41	2 lines disconnect and 2 gens trip in north Ohio,1868MW	
21. 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	
22. 4:10:46 – 4:10:55	New York splits east-to-west. New England and Maritimes separate from New York and remain intact. (power swing+UFLS)	
23. 4:10:50 – 4:11:57	Ontario separates from NY w. of Niagara Falls & w. of St. Law. SW Connecticut separates from NY ,blackout .(relay operation ,ULFS)	

IMPACT

	Location	Date	MW Lost	Duration	People affected	Approximate cost
1	US-NE	11/9/1965	20000	13 hours	30 million	
2	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	
5	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			
11	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
8	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	

PRE-EVENT CONDITIONS

Location	Date	Weather	Loading	Topology
US-NE	11/9/1965	mild	normal	normal
US-NE	7/13/1977	Stormy	normal	weakened (1 major tie feeder, 1 major gen out)
France	12/19/1978		Heavy	Normal
West Coast	12/22/1982	windy	normal	normal
Sweden	12/27/1983			
Brazil	4/18/1984			
Brazil	8/18/1985			
Hydro Quebec	4/18/1988	Freezing rain	normal	normal
US-West	1/17/1994	mild	normal	normal
Brazil	12/13/1994			
US-West	12/14/1994	cold	Heavy	normal
Brazil	3/26/1996			
US-West	7/2/1996	Hot 38C	Heavy	Normal
US-West	7/3/1996	Hot 38C	Stressed	Normal
US-West	8/10/1996	Hot 38C	normal	weakened (three 500 KV line sections out of service
MAPP, NW Ontario	6/25/1998	stormy	heavy	normal
San Francisco	12/8/1998	normal	normal	normal
Brazil	3/11/1999			
Brazil	5/16/1999			
India	1/2/2001			
Rome	6/26/2003	Hot	heavy	weakened
US-NE	8/14/2003		heavy	Weakened (3 gens out of service)
Denmark/Sweden	9/23/2003		heavy	Weakened (1 nuclear unit out for maintenance)
Italy	9/28/2003		heavy	Weakened (trip of Swiss 380 KV line Mettlen-Lavorgo)
Croatia	12/1/2003	wind,cold,ice, rain	normal	weakened
Greece	7/12/2004	Hot	Heavy	weakened(4 150KV, a 125 MW & 300MW unit out)
Moscow/Russia	5/24-25/2005	Hot	Heavy	Weakened (loss of a cogen plant)

TRIGGERING EVENTS

Location	Date	Cause	How many elements lost (N-1, N-2, etc)
US-NE	11/9/1965	Faulty Relay setting	N-1
US-NE	7/13/1977	Lightening	N-2
France	12/19/1978		
West Coast	12/22/1982	500 KV Tr tower failed due to high winds	N-1
Sweden	12/27/1983	Disconector Failed	N-2
Brazil	4/18/1984	Xmer shutdown due to overload, and load increase	N-1
Brazil	8/18/1985	1 phase to grd short ckt+ in-advertent protection operation	N-2
Hydro Quebec	4/18/1988	Ice causes flashover	N-3
US-West	1/17/1994	Earthquake	many
Brazil	12/13/1994	human error	2 D.C. bipoles blocked
US-West	12/14/1994	Single phase to gnd fault, relay misop.	N-2 (inadvertent of additional 345KV ckt)
Brazil	3/26/1996	human error+inadvertent prot. operation	N-1
US-West	7/2/1996	Tree Flashover followed by relay misop.	N-1
US-West	7/3/1996	Tree Flashover	N-1
US-West	8/10/1996	Tree Flashover	N-1
MAPP, NW Ontario	6/25/1998	lightening	N-1
San Francisco	12/8/1998	human error	no of lines
Brazil	3/11/1999	Bus Fault	Multiple lines (> N-6)
Brazil	5/16/1999	Inadvertent protection operation	Many
India	1/2/2001		
Rome	6/26/2003	high load demand	
US-NE	8/14/2003	Brush fire on a line (outage)	N-1
Denmark/Sweden	9/23/2003	Nuclear Plant trips (technical problem), double busbar fault	N-1
Italy	9/28/2003	Tree Flashover	N-1
Croatia	12/1/2003	Breaker failure	N-1
Greece	7/12/2004	Load Increasing	N-1
Moscow/Russia	5/24-25/2005	Load Increasing/Xmer bursting	

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	Transformer	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	Transformer	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

NATURE OF COLLAPSE

Location	Date	Nature of Collapse
US-NE	11/9/1965	Successive tripping of lines
US-NE	7/13/1977	Successive tripping of lines and generators
France	12/19/1978	Voltage collapse , loss of synchronism
West Coast	12/22/1982	Successive line tripping from mechanical failure of transmission lines+protection coordination scheme failure
Sweden	12/27/1983	Voltage collapse
Brazil	4/18/1984	Voltage Collapse
Brazil	8/18/1985	Successive tripping of lines and generators
Hydro Quebec	4/18/1988	Succesive tripping of lines and generators
US-West	1/17/1994	Massive loss of Trans Resources
Brazil	12/13/1994	Voltage, frequency collapse
US-West	12/14/1994	Transient Instability, Successive tripping of lines and Voltage collapse
Brazil	3/26/1996	Simultaneous and successive tripping of lines
US-West	7/2/1996	Successive tripping of line, generators and also volatage collapse
US-West	7/3/1996	Voltage collapse
US-West	8/10/1996	Voltage collapse
MAPP, NW Ontario	6/25/1998	Successive tripping of lines
San Francisco	12/8/1998	Voltage and frequency collapse
Brazil	3/11/1999	Successive tripping of lines
Brazil	5/16/1999	Simultaneous and successive tripping of lines
India	1/2/2001	
Rome	6/26/2003	Disconnection to interruptible customers and users
US-NE	8/14/2003	Successive tripping of lines(400), generators(531). Voltage Collapse
Denmark/Sweden	9/23/2003	Voltage collapse
Italy	9/28/2003	Voltage collapse, Frequency collapse
Croatia	12/1/2003	Voltage collapse
Greece	7/12/2004	Voltage Collapse
Moscow/Russia	5/24-25/2005	Successive tripping of lines, generators and Voltage collapse

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

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

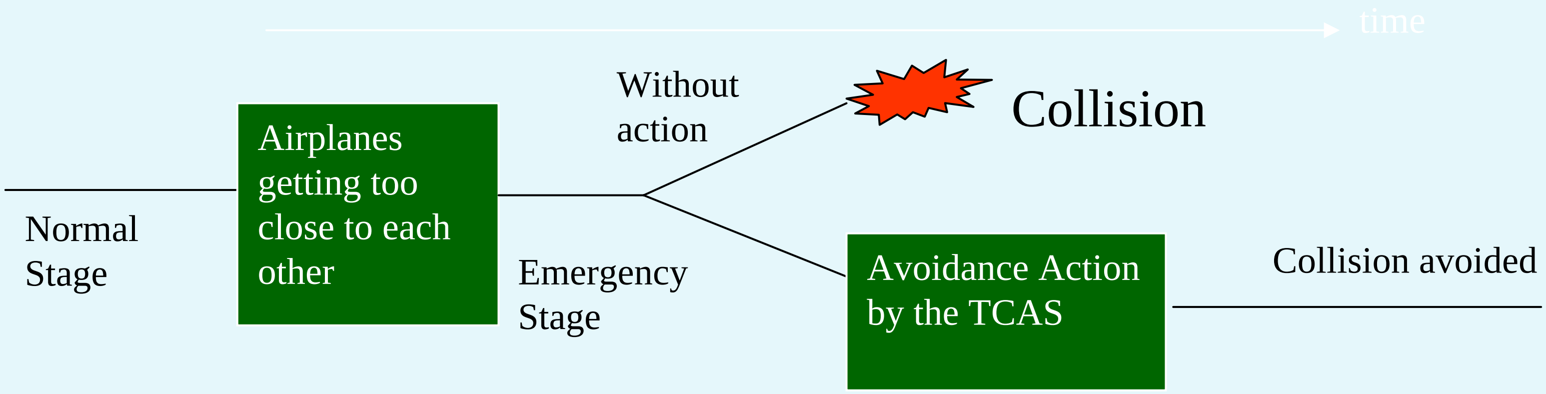
Scenario for 50% of blackouts

1. **Weakened conditions: Heavy load, and/or one or more gen or cct outage possibly followed by readjustments**
2. **Triggering event: One or several components trip because of fault and/or other reasons;**
3. **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**
4. **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**

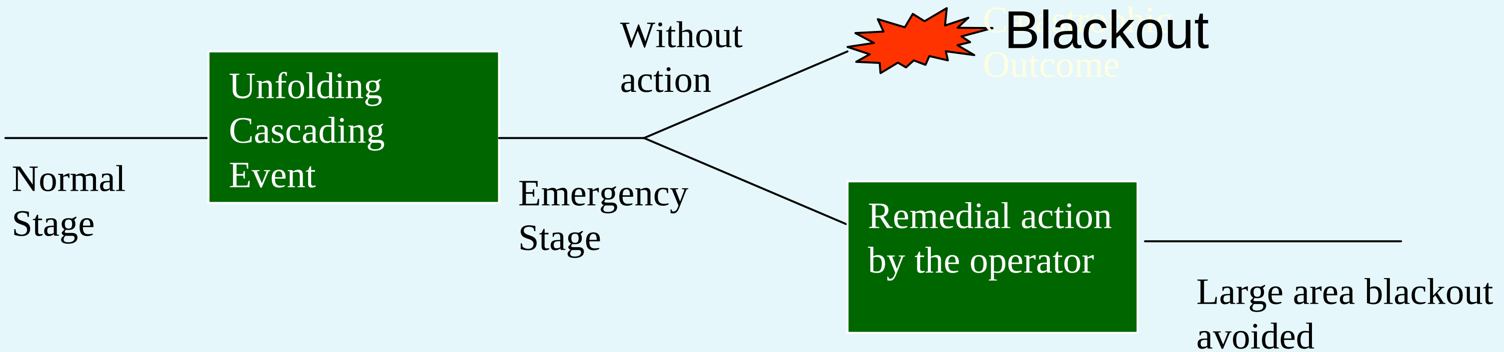
Approaches to reduce frequency/severity of high consequence events

- Transmission & generation investment for reliability
- Condition monitoring & strategic maintenance
- Automated response: SPS
- Automatic islanding
- Wide area monitoring, control and protection
- Use a minimum risk corrective action policy
- Training & preparedness: a new EMS-operational tool
- Automated restoration procedures

A New Operator's Tool: An Analogy to Air Traffic Control



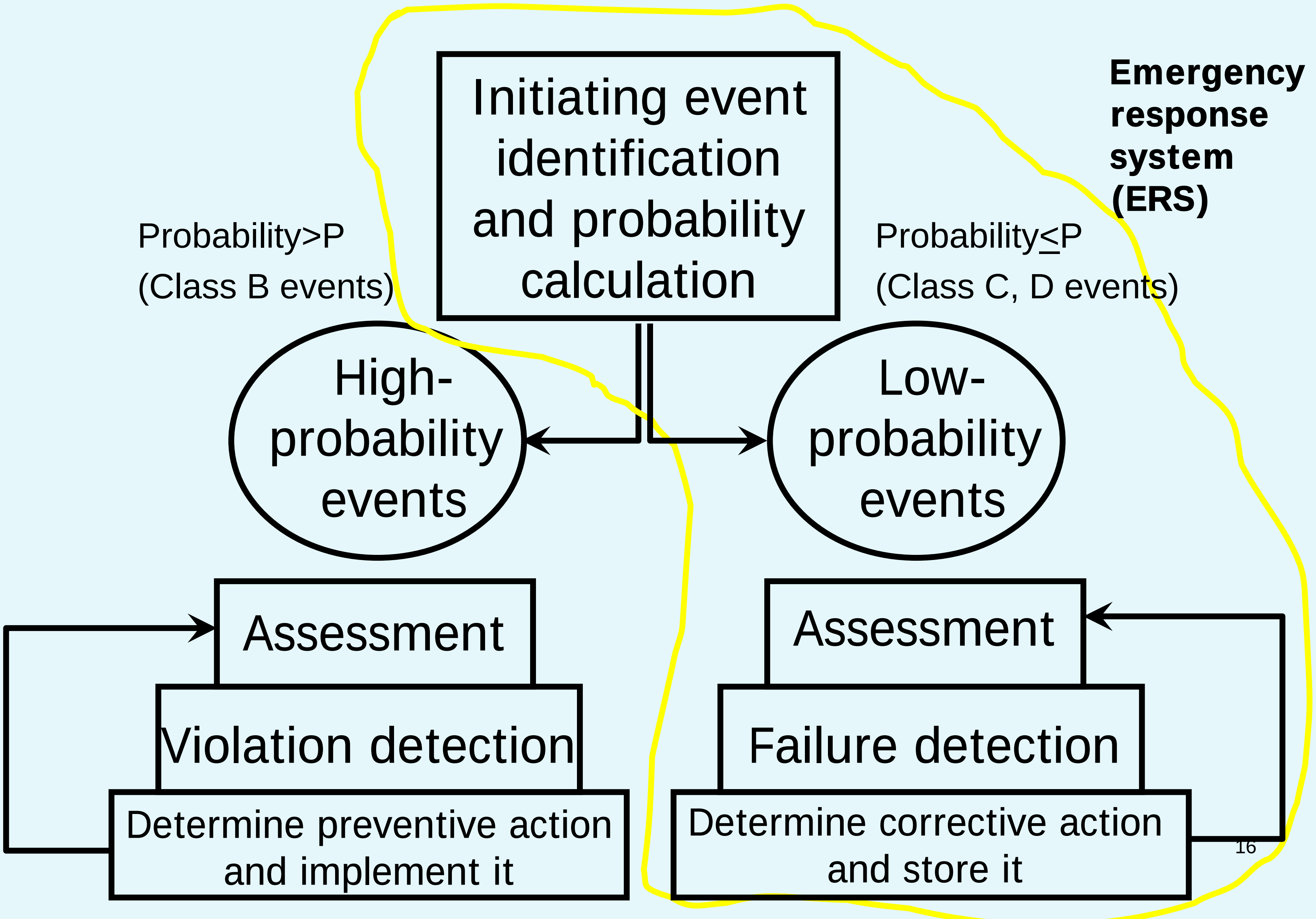
Traffic Alert and Collision Avoidance System



Emergency Response System

www.mitrecaasd.org/work/project_details.cfm?item_id=153

Preventive/corrective action paradigm



Operational approach to blackout mitigation

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

Corrective control: operational solution to blackouts.

- Actions determined on-line, in anticipation of events, to be actuated through operator upon event occurrence

Need new EMS Function

- ERS: decision support to unfolding events
- ERS-TS: blackout avoidance training

Operational approach to blackout mitigation

The Emergency Response System:

➔**Continuously identifies catastrophic event sequences together with actions operators can take to mitigate them**

➔**Intelligent selection of triggering events**

➔**Uses current or forecasted conditions**

➔**Based on mid-term (hours) simulation tool**

➔**Must have protective relaying modeled**

➔**Stores results for fast retrieval should event occur**

Selection of triggering events

- Problem: Identify triggering events to assess
- Strategy: select triggering events based on substation topology using switch-breaker data already existing in topology processor

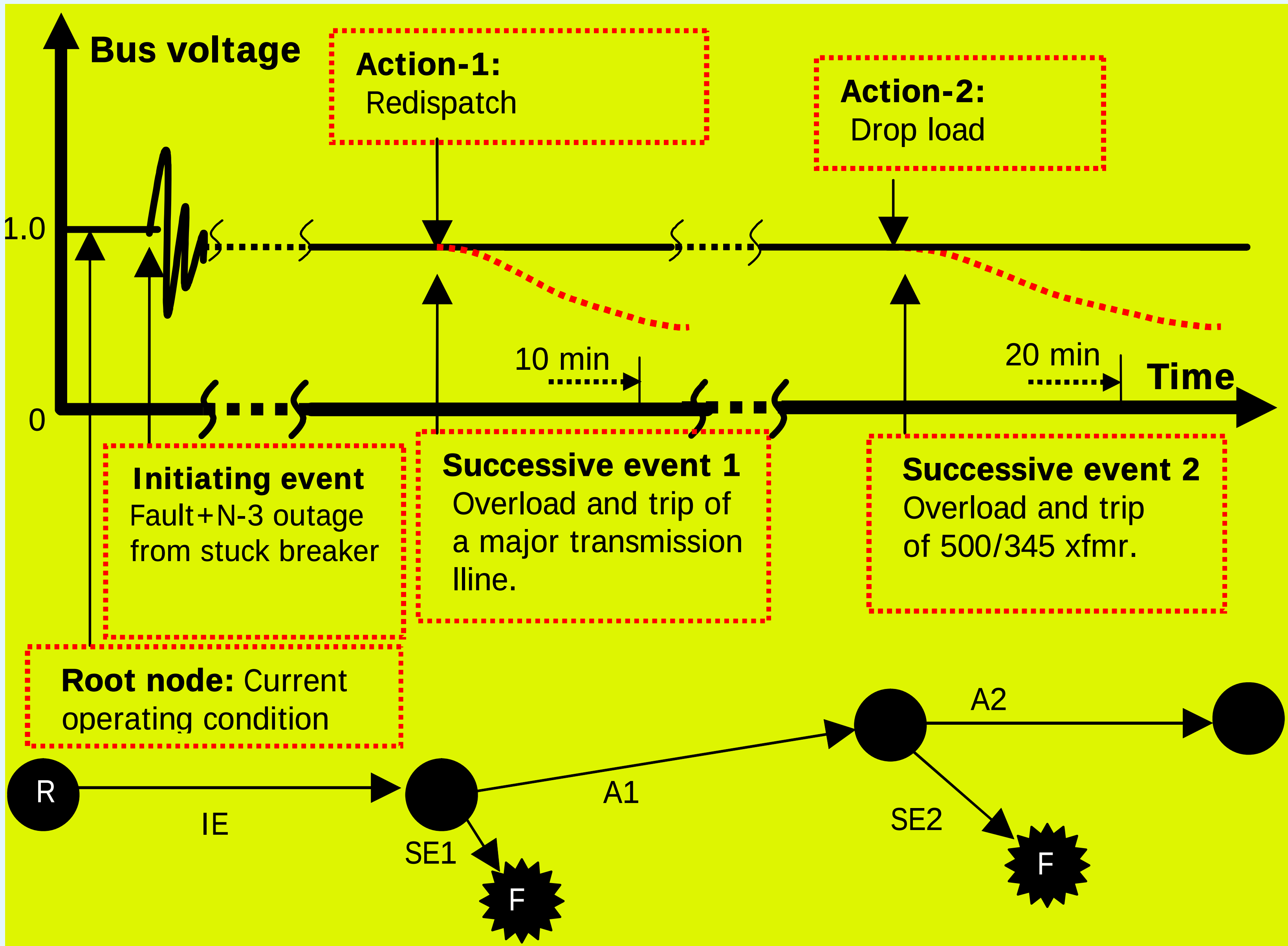
A functional group is a group of components that operate & fail together as a result of breaker locations within the topology that interconnects them.

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

High-Risk Triggering Events

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

Simulation, storage, & retrieval



Simulator attributes

- 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
- 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

Final Comments on Operational Approach to Blackout Mitigation

- Number of major blackouts doubles every 10 years
- Various approaches to reduce frequency, mitigate severity
- Operators are last line of defense; they need better tools
- Preparing operators for rare events is fundamental to operating engineering systems having catastrophic potential; it has precedent in air traffic control, nuclear, & process control.
- Described approach is a generalization of already-existing event-based special protection systems, except here
  - response continuously developed on-line
  - actuation is done through a human