Operational Defense of Power System Cascading Outages

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Cascading Failures & Blackouts
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Overview

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

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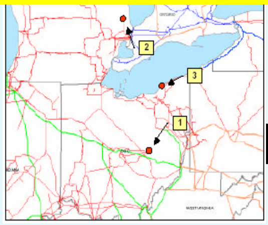
1. 12:05 2. 1:14 3. 1:31	Conesville Unit 5, 375 MW Greenwood Unit 1, 785 MW Eastlake Unit 5, 597 MW, overexcitation	Weakening conditions
4. 2:02	Stuart – Atlanta 345 kV (brush fire)	Triggering event
5. 3:05 6. 3:32 7. 3:41 8. 3:39-4:05 9. 4:05	Harding-Chamberlain 345 kV (tree) Hanna-Juniper 345 kV (tree)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



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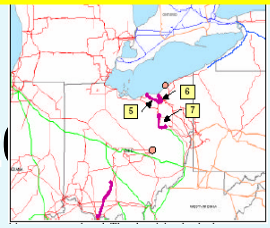

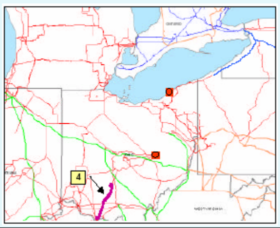

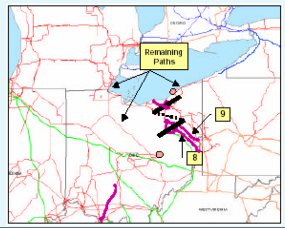

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10. 4:08:58	Galion-Ohio Central-Muskingum 345 kV (zone 3)	
11. 4:09:06	East Lima-Fostoria Central 345 kV (zone 3)	
12. 4:09:23-4:10:27	Kinder Morgan (rating: 500 MW; loaded to 200 MW)	
13. 4:10	Harding-Fox 345 kV	
14. 4:10:04 – 4:10:45	20 generators 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	
	US-NE	7/13/1977	6000	22 hours	3 million	300 million
2	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			
	US-West	7/2/1996	11743		1.5 million	
11	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	
9	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	11/412006	> 6400	1 Hour	15 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)
European Blackout	11/4/2006		normal	weakened as no of power plants shut down

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TRIGGERING EVENTS

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	
European Blackout	11/4/2006	human error	many

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

NATURE OF COLLAPSE

Location	Date	Causes of secondary, pre-collapse events
US-NE	11/9/1965	Proper protection operation (as designed) (overload protection)
US-NE	7/13/1977	Lightening , Proper protection operation (overload+gen protection)
France	12/19/1978	Proper protection operation (overload protection,out of step relays)
West Coast	12/22/1982	Primary and secondary protection & communication failure
Sweden	12/27/1983	Proper protection operation (overload protection), underfreq LS failure
Brazil	4/18/1984	Simultaneous tripping of 7 ckts and Xfmer
Brazil	8/18/1985	Protection failure (SPS setting)
Hydro Quebec	4/18/1988	Communication failure followed by load shedding protection failure
US-West	1/17/1994	Earthquake
Brazil	12/13/1994	Inefficient Protection, loss of synchronism
US-West	12/14/1994	Proper protection operation (overload protection)
Brazil	3/26/1996	Proper protection operation
US-West	7/2/1996	Proper protection operation (gen protection), relay misoperation
US-West	7/3/1996	Relay Misoperation
US-West	8/10/1996	Trees, protection (relay) failure
MAPP, NW Ontario	6/25/1998	Lightening trip another 345 kV line followed by proper ovrload protection
San Francisco	12/8/1998	No local protection, topology,delayed remote protection
Brazil	3/11/1999	Proper protection operation (overload protection)
Brazil	5/16/1999	Inadvertent Protection operation
India	1/2/2001	
Rome	6/26/2003	High Load, low generation, reduction in import
US-NE	8/14/2003	Proper protection operation
Denmark/Sweden	9/23/2003	Switching device breaks ,Proper protection operation (generator and overload protection)
Italy	9/28/2003	Unsuccessful reclosing, Tress, loss of synchronism, dynamic intercaction leading to voltage collapse
Croatia	12/1/2003	Protection failure
Greece	7/12/2004	Proper protection operation
Moscow/Russia	5/24/2005	6 lines from HV substation tripped due to faults and overloading
European Blackout	11/4/2006	Proper protection operation

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

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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

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Scenario for 50% of blackouts

1. **Weakened conditions: Heavy load, and/or one or more gen or cct outage possibly followed by readjustments**
2. **Initiating 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, gens**
   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 goes under-frequency and/or under-voltage.**
   b. **Components begin tripping quickly**
   c. **Uncontrolled islanding and wide spread blackout.**

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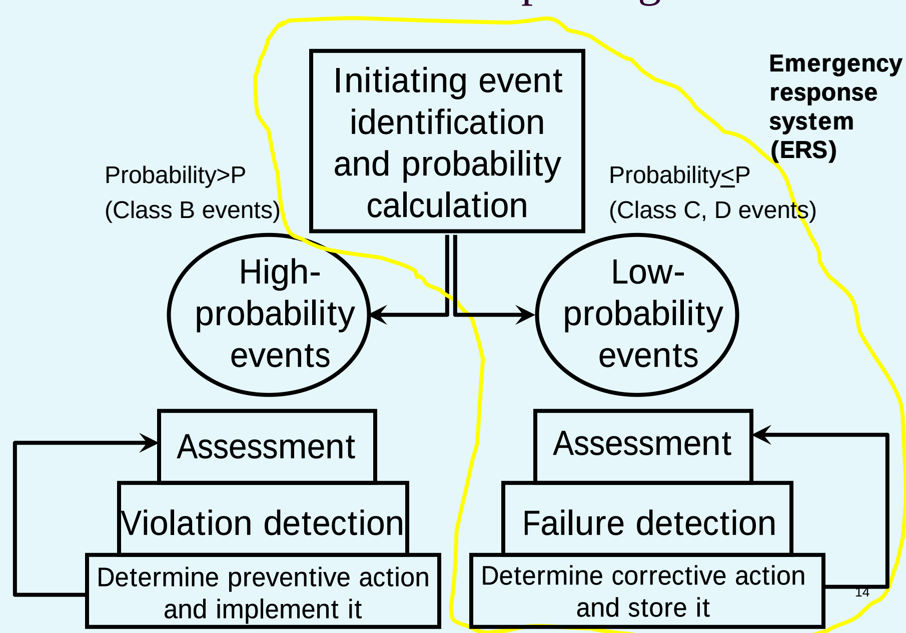
Preventive/corrective action paradigm



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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

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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

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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

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Contingency Selection

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.

Graph search identifies five types of initiating events:

1. Functional group tripping , ~ P
   - Proper relay tripping, may trip multiple components
2. Fault plus breaker failure to trip, ~ 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, ~ P^2
   - Inadvertent tripping of backup breaker to a primary fault
4. Common mode events, ~ 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, ~ $P^2 \rightarrow$ ~ P^3

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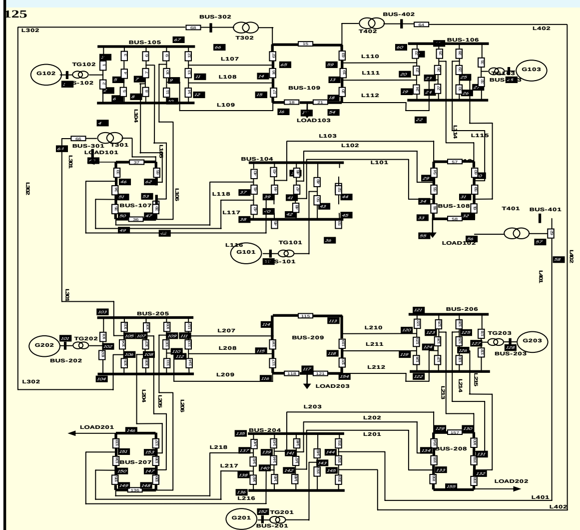
Contingency Selection



Number of contingencies of type N-k resulting from a single fault (Order P) for 21 Bus System

k	1	2
No.	42	6

Number of contingencies of type N-k resulting from a fault/breaker failure (order P^2) for 21 Bus System

k	1	2
No.	59	67

Number of contingencies of type N-k resulting from ITC (Order P^2) for 21 Bus System

k	2	3
No.	86	39

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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

Searching Time to Identify Contingencies (2.4Ghz Pentium)

System Scale (No. of Buses)	24	1549	5,000	10,000
Time (Second)	0.01	0.63	2.08	4.17

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Simulator

1. **Seamless interface with & simulation on node-breaker model for proper identification of initiating & successive events**
2. **Model full range of dynamics:**
   - **Fast dynamics, including generator, excitation, governor**
   - **Slow dynamics, including AGC, boiler, thermal loads**
3. **Model condition-actuated protection action that trips element**
   - **Generator: field winding overexcitation, loss of field, loss of synchronism, overflux, overvoltage, underfrequency, and undervoltage**
   - **Transmission: impedance, zone 3, out-of-step**
4. **Identifies islanded condition and continues simulation in each**
5. **Saves & restarts from conditions at any time**
6. **Failure detection and prevention**
7. **SPEED is essential:**
   - **Adaptive time step using "theta" implicit integration method**
   - **Intelligent Jacobian updating**
   - **Sparsity-based coding and multi-frontal solver for Ax=b**
   - **Deploying on an IBM BlueGene supercomputer**

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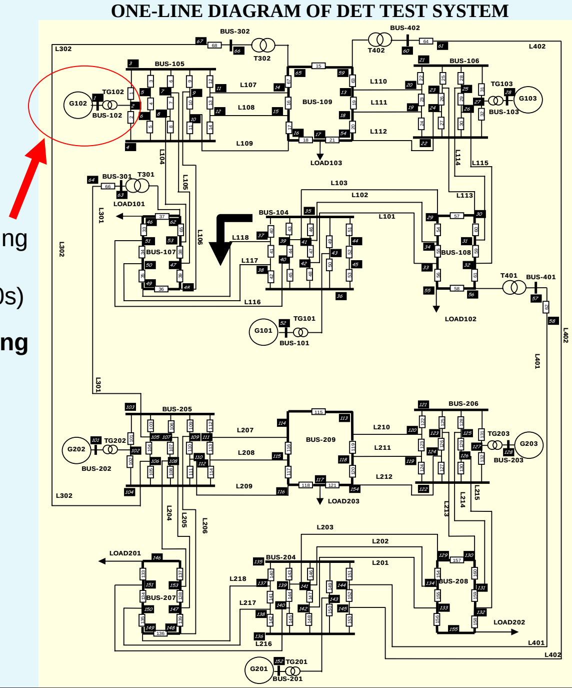
Simulator is written in C++

ONE-LINE DIAGRAM OF DET TEST SYSTEM



G102 (initiating generator trip at *t*=300s)

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

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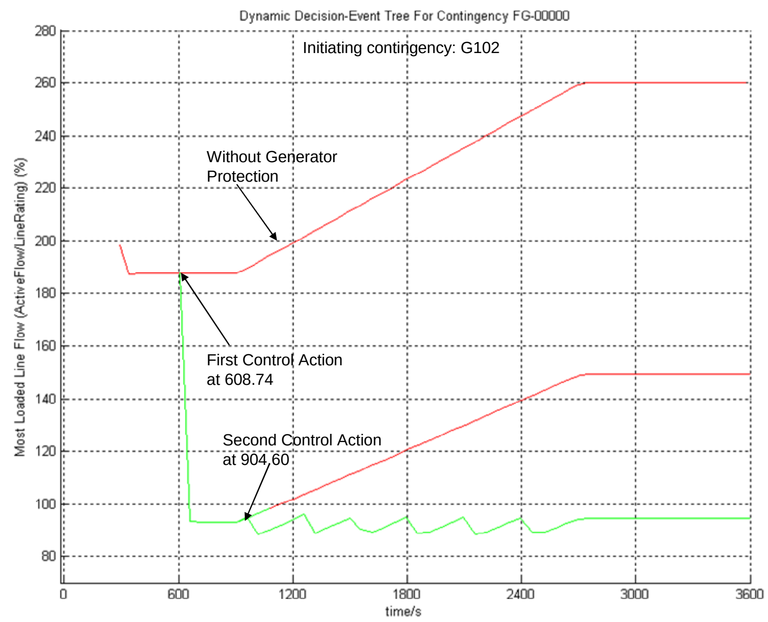

Final Comments on Operational Approach to Blackout Mitigation

- 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

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