August 14, 2003 Blackout and Subsequent Investigation

NERC/TVA Stability Workshop
May 23, 2007
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Summary of August 14 Blackout

**Impacts**
- 8 states/2 provinces
- Over 50 million people
- 60-65,000 MW
- 96+ hours to restore
- Manufacturing disrupted
- 531 generators tripped
  - 19 nuclear generators at 10 plants

**Statistics**
- Line trips began at 3:05 PM
- Cascading began at 4:06 PM
- Instability began at 4:10:37 PM
  - Lasted approximately 12 seconds
- Thousands of discrete events
Key Findings

- Inadequate system planning and design studies, operations planning, facilities ratings, and modeling data accuracy
- Operating with insufficient reactive margins
- More effective system protection and controls could slow or minimize spread of cascading outage
- Problems from prior blackouts were repeated
The Old - Repeated

● The three “T’s”
  ▪ **Tools** – for the operator to monitor and manage the system
  ▪ **Trees** – vegetation management to prevent tree contacts
  ▪ **Training** – operators need to provided training and drills to be prepared to respond to system emergencies
Key Findings

\[ h \geq \int i^2 R \frac{dw}{dt} + x \sum_{1}^{n} b \]

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The New

- **Failure of Tools**
  - Information Technology support – communications
    - “Game Over”
- **Failure of “Defense in Depth”**
- **Generation Protection**
  - Consideration of performance during dynamic and extreme low voltage events
  - Coordination of plant controls with the transmission system
Multiple Concurrent Software Failures

1. FirstEnergy alarm failures
2. FirstEnergy remote EMS terminal failures
3. MISO state estimator failures for L/O Bloomington-Denois Creek 230 kV and Stuart-Atlanta 345 kV
4. MISO topology processor failure – did not recognize Harding-Chamberlin 345 kV line trip when breakers were open
Control Area (CA) Computer Failures

- 2:14 PM - alarm logger fails and operators are not aware
- 2:41 PM - server hosting alarm processor and other functions fails to backup - IT staff is auto-paged.
- 2:54 PM - backup server fails (2 of 4 servers down)
  - 2 servers continue to function but with long refresh (~59 second)
  - selected CA data continues to be sent to other control centers
  - unidentified Harding - Chamberlin 345kV line outage at 3:05 PM
Control Area (CA) Computer Failures

- 3:08 PM - IT warm reboot of servers appears to work but alarm process not tested and still in failed condition
- CA Operators are now ‘blind’ & lose situational awareness
- Reliability Coordinator (RC) computers are still working.
Reliability Coordinator Tools (MISO)

- “state estimator” failed due to data errors, & periodic automatic restart turned OFF
- monitoring tools did not have real-time line information to detect growing overloads
- not within contingency limits from 3:06 - 4:06
  - “missed” Harding - Chamberlin line outage at 3:05 PM
  - did not have wide area map-board for the above
  - state estimate & contingency analysis not successful.
- To monitor the power system, MISO was using software that was considered “under development and not fully mature”
Outline of Presentation

1. Description of the Sequence of Events

2. Modeling the Disturbance
   a) Determination of Sequence of Events
   b) Analysis of What Happened
   c) Development of Countermeasures for Future Disturbances
Outage Sequence of Events

Transmission Map Key

Transmission Lines
- 765 kV
- 500 kV
- 345 kV
- 230 kV
Eastlake #5 Generator Trip 1:31:34 PM
Eastlake #5 Trip

Exciter Control trips to manual and backs off overloaded MVAR output

Rated MVAR Limit

Exciter System trips completely off as operator returns it to automatic voltage control
Power System High Level Sequence

- Premature failure of three 345 kV lines
  - starting at 3:05 PM, three 345 kV line outages within 36 minutes due to tree branches under conductors

- Northern Ohio 138kV cascade began
  - started 3:39 PM - caused by above premature failures

- Northern Ohio 345kV high speed cascade of overloaded lines 4:05:57 - 4:09:07 PM
  - accelerated by Zone 3 directional distance relays

- Eastern Interconnection Separates by 4:11 PM
Major Path to Cleveland Blocked after Loss of Sammis-Star 345 kV Line  4:05:57.5 PM
345 kV Lines Trip Across Ohio to West
4:08:59 - 4:09:07 PM
Generation Trips
4:09:08 – 4:10:27 PM
Voltage Collapses in Southern Michigan
4:09:00 – 4:10:30 PM

Michigan Voltages

90 sec.

345 kV Voltage

Argenta
Battlecreek
Thetford
Tompkins

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345 kV Cascade Moves North into Michigan
Argenta-Battle Creek Lines Lines Trip 4:10:36 – 4:10:37PM
NY to Ontario 345kV Line Flows at Niagara
Progressively Worsening Stability Conditions

New York to Ontario 345 kV Line Flow at Niagara
(does not include 230 kV line flow)
And Then...Things Got Nasty!!
New Phase Begins - “Transient Instability”
Three 345 kv Lines Trip from 4:10:37.5 - 4:10:38.6 PM
Power Transfers Shift at 4:10:38.6 PM
Michigan and Ohio Separate
Recorded Beaver Bayshore
Simulated Beaver Bayshore

Island formation complete

60 Hz
Caniff
Monroe 1-2
Monroe 3-4

60 Hz

TIME (SECONDS)

DETROIT AREA FREQUENCIES
Monroe – Majestic – Allen Jct. 345 kV Line Trips at Monroe

Blackfoot – Madrid & Stephens -- Caniff 345 kV Lines Trip

Caniff

Monroe 1-2
Monroe 3-4
Southeast Michigan Separates into Two Pieces
4:10:39.268 – 4:10:41.105 PM
Eastern Michigan as Observed from Ontario
Detroit Units Slip Poles

Keith-Waterman (J5D) 230 kV - Tie Line

Severe Voltage Depression in Downtown and Southern Detroit Region

Toledo/Cleveland Island Separates from Detroit

Detroit Area Generation Pulls Out of Synch and Slips 2 Poles as Frequency Increases to ~62 hz

Significant Generation Loss and/or Transmission Separation in Detroit

Remaining Detroit Generation Slips 2 Poles as Frequency Falls at Keith-Waterman Trips at 16:10:43.2

Classical Stability

Seconds from 16:10
Meanwhile in New Brunswick...
Keswick Frequency
Line 3001 MW
Northeast Island Separates from Eastern Interconnection 4:10:43 – 4:10:45 PM

North of Lake Superior
New England Separates from Eastern Interconnection  4:10:46 – 4:10:48 PM

North of Lake Superior
New York Splits Internally
4:10:48.823 – 4:10:49.600 PM

North of Lake Superior
New York – Ontario Separation
4:10:49.420 – 4:10:49.760 PM

North of Lake Superior
Frequency in Ontario and New York

Northwest Ontario Stays with Manitoba
Beck Re-Separates from Interior Ontario System

Beck and St. Lawrence Stay Separated from Interior Ontario But Connected to New York State

Beck Reconnects to Interior Ontario System
Beck and St. Lawrence Separate from Interior Ontario System

Time in Seconds from 16:10:00

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End of the Cascade

Area affected by blackout
Service maintained in isolated pockets
Modeling and Studies Work
Modeling & Studies Work

- **Powerflow Modeling**
  - Study of disturbance from 3:05 PM (just before Harding-Chamberlin line trip) to 4:05:50 PM (just before Sammis-Star line trip)
  - Powerflow study concluded at 4:06 PM because case would no longer converge

- **Dynamics Modeling**
  - Study of disturbance from 4:05:50 PM to end of cascade
  - Mid-term dynamics and transient stability
Powerflow Analysis

- Development of powerflow case to represent system conditions at 3:05 PM (immediately before Harding-Chamberlin outage)
  - No straightforward method of transferring historical power system data from control areas into an interconnection-wide powerflow
  - Development of powerflow case required many months
  - Resulting case less than perfect
Simulated 138 kV Line Loadings

% of Normal Ratings (Amps)

Outages

- Dale-W.Can 138 kV
- W.Ak-PV Q22 138 kV
- Cham-W.Ak 138 kV
- E.Lima-N.Fin 138 kV
- CantC Xfmr
- W.Ak-PV Q21 138 kV
- Babb-W.Ak 138 kV
- E.Lima-N.Lib 138 kV

NERC
Simulated 345 kV Line Loadings

- Sammis-Star 345 kV
- CantC-Tidd 345 kV
- Star-S.Cant 345 kV
- Hanna-Jun 345 kV
- Hard-Chamb 345 kV
- CantC Xfmr 138 kV
- Bkr 138 kV
Power Flow Modeling Problems

- **Line Rating Discrepancies**
  - Sammis-Star 345 kV line rating different for PJM, AEP, MISO, & FE

- **Topology Errors — Dating back to 1991**
  - No feedback loop in MMWG/SDD case creation process

- **Power Factor**
  - Optimistic reactive power loads

- **Generator Reactive Limits**
  - Not verified with actual capability

- **Model Quality**
  - Systemic problem of model and data quality control

- **Powerflow Program Version Discrepancies**
Modeling & Studies Work

● Successful Forensic Dynamic Analysis
  ▪ Able to duplicate measured system response through 16:11
  ▪ Far beyond expectations
  ▪ Significant modeling lessons learned
  ▪ Validation of Sequence of Events
  ▪ Understanding of Eastern Interconnection behaving as a single system
  ▪ Set stage for further study of “what ifs”
Simulated Ontario-Michigan Data
Recorded
Monroe 3-4
Monroe 1-2

Simulated
Monroe 3-4
Monroe 1-2

60 Hz

TIME (SECONDS)

MONROE BUS FREQUENCIES
Recorded
Monroe 3-4
Monroe 1-2

Simulated
Monroe 3-4
Monroe 1-2

Monroe – Majestic – Allen Jct. 345 kV Line Trips at Monroe

Blackfoot – Madrid & Stephens -- Caniff 345 kV Lines Trip
Dynamics Modeling

- Accurate Models Necessary
  - One family of exciter models was found to have an unstable step response
  - Some units’ models were unstable due to bad data in the models
  - Generators dispatched beyond real and reactive limits
  - Incorrect machine MVA base values
  - No dynamics data for most small units
    - Generic generator data used in the MMWG case
  - No standard of formats for powerflow and dynamics data
Dynamics Modeling

● Program deficiencies
  ▪ Program does not allow modeling of underfrequency load shedding (UFLS) and undervoltage load shedding (UVLS) on the same bus
  ▪ Some models caused the program to freeze or crash
  ▪ v. 29 available but not considered reliable

● Program features
  ▪ Program allows a simulation to be stopped during the middle of a run and restarted at a later time
Dynamics Modeling Innovations

- New Models Developed
  - Simulate phenomena not normally represented in standard dynamics program models
  - Modified dynamic load model
    - More responsive to voltage deviations
  - Ad hoc LTC model
    - Represent load behavior over 60 s – 90 s
  - Modified existing generator models
    - Represent generator mechanical overspeed protection systems
Replication of the Disturbance

● Iterative Process

1. Run simulation with best available event times and information
2. Compare with available recordings and data
3. Adjust simulation and/or SOE according to observed discrepancies
4. Return to step 1
Replication of the Disturbance

- Parametric Analysis
  - Some dynamic model parameters (especially load) are not precisely known
  - Several simulations performed using a range of values for these parameters
  - Parameter value(s) selected based on best overall match with recorded data
  - Does not imply that these parameter values are appropriate for other studies
Dynamic Recording Devices

- Non-synchronized Disturbance Recorders
  - Monumental forensic analysis required
- Dynamic data supplied in multiple proprietary formats
  - Some files had format errors
- Ad-hoc software written to extract frequency and line power flows (real and reactive) from digital fault recorder (DFR) data
Digital Fault Recording Devices

- All such devices should ...
  - Be GPS time synchronized.
  - Include a frequency trace.
  - Be periodically checked for calibration and operability
  - Have all data provided in IEEE/ANSI Comtrade standard C37.111-1999 format
  - Have file names in the IEEE common naming convention.
- Add digital readout of frequency requirement to the Comtrade standard.
- The disturbance data recording system should facilitate data storage and archiving capabilities.
NY Phasor Measurements (PMUs)

- Power Flow (MW)
  - PY to IMO
  - PJM to NY
  - NE to NY
  - Ont to Mi

- Frequency (Hz)
  - NY West
  - NY East
  - Lambton

Events:
- NY Separates from NJ
- NY and NE Separate
- Split complete between East and West NY
- Ontario splits from West NY
- Ontario reconnects with West NY
Ontario Power System Dynamic Recorders (PSDRs)

Time

- 16:10:30
- 16:10:40
- 16:10:50
- 16:11:00

Power Flows (MW)

- New York into Ontario
- Ontario into Michigan
- PJM into New York
- New York into New England

Start of split between East and West MI
- 16:10:36
- Detroit, Cleveland separated from W. MI.
- Cleveland cut off from PA
- NY separates from PA
- NY separates from Ohio, Indiana, Illinois

1650 MW Detroit generation trips

- 16:10:42
- Ontario splits from West NY

Split complete between East and West NY

16:10:49
- NY and New England separate

16:10:50
- Ontario reconnects with West NY

16:10:56
- Ontario into Michigan

16:11:00
- Ontario reconnects with West NY

Frequency (Hz)

- Lambton ONT-MI
- NY-East
- NY-West

16:10:30 to 16:11:00
View Into Detroit from Lambton

Keith-Waterman Trips

Location of Distant Asynchronous Island

Hampton-Pontiac Trips

Thetford-Jewell Trips

Detroit Area Generation Trips at 40.5 and 41.3

Toledo/Cleveland Island Separates from Detroit
Use of Non-synchronized Data

- Frequency, frequency spikes, and step changes in voltage and current used to identify events in a synchronized data record.
- These spikes and step changes then matched to non-synchronized data records to determine the skew of the non-synchronized clock.
- Identification of events in recordings aided by the dynamic simulation.
- “Daisy-chaining” of multiple recorders.
East Towanda – East Sayre 115 kV line trip

Tiffany – Lenox 115 kV line trips

MW Flow
Mvar Flow
East Towanda – East Sayre 115 kV line trip

MW Flow
Mvar Flow
Homer City – Stolle Road 345 kV line trip

Homer City – Watercure 345 kV line trip

Moshannon – East Towanda 230 kV line trip

MW Flow

Mvar Flow

TIME (SECONDS)

FRI, FEB 10 2006 17:43
P&Q E. TOWANDA-HILLSIDE
Ashtabula 345/138 kV transformer trip

Perry – Ashtabula – Erie West 345 kV line trip at Perry

Homer City – Watercure 345 kV line trip

Homer City – Stolle Road 345 kV line trip

Keystone – Homer City 230 kV line MW

Keystone – Homer City 230 kV line Mvar
Angular Separation Analysis
Dynamic Analysis Finding

- Cascade could have been arrested by dropping all of Cleveland load prior to loss of Argenta – Battle Creek / Argenta – Tompkins 345 kV Lines
  - Nothing then measurable to suggest taking such action
  - Angular separation analysis showed possible trigger (~90 second window)
Simulation Angular Measurement Points
Angular Separation Analysis

Normal Angle ~ -25°

Reference:
Browns Ferry
16:10:37 to 16:10:47

- Detroit out of Synch
- Western MI
- NY-PJM Separation
- Cleveland Separation
- NY
- NJ
- Ontario

Degrees
System-Wide Analysis & Tools

- Power flow and dynamic analyses point toward
  - Need for situational awareness of line outages and their influence on operational security
  - Need for monitoring locational reactive reserves and resultant voltage profiles
  - Improved situational awareness for operators though early warning system based on zonal angular separation
    - Need for phasor measurements for wide-area
Questions?