PDHonline Course E346 (3 PDH)

System Failure – Anatomy of a Blackout : Part II – Cascading Failure of the Power System

Instructor: Lee Layton, PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

System Failure
Anatomy of a Blackout
Part II
Cascading Failure of the Power System

Lee Layton, P.E

Table of Contents

This course is a based on a North American Electric Reliability Council report, Technical Analysis of the August 14, 2003 Blackout: What Happened, Why, and What Did We Learn? The Report has been edited for brevity and clarity for this course.

Preface

On August 14, 2003, just after 4 p.m. Eastern Daylight Time (EDT), the North American power grid experienced its largest blackout ever. The blackout affected an estimated 50 million people and more than 70,000 megawatts (MW) of electrical load in parts of Ohio, Michigan, New York, Pennsylvania, New Jersey, Connecticut, Massachusetts, Vermont, and the Canadian provinces of Ontario and Québec.

Although power was successfully restored to most customers within hours, some areas in the United States did not have power for two days and parts of Ontario experienced rotating blackouts for up to two weeks.

This course looks at the conditions on the bulk electric system that existed prior to and during the blackout, and explains how the blackout occurred. Note that since this report was originally written, several of the companies and organizations mentioned in the report have merged or reorganized.

Immediately following the blackout, NERC assembled a team of technical experts from across the United States and Canada to investigate exactly what happened, why it happened, and what could be done to minimize the chance of future outages. The scope of NERC's investigation was to determine the causes of the blackout, how to reduce the likelihood of future cascading blackouts, and how to minimize the impacts of any that do occur. NERC focused its analysis on factual and technical issues including power system operations, planning, design, protection and control, and maintenance.

This course is Part II of a two part series about the August 14, 2003 blackout. Part I covered the events leading up to the black and gave an overview of the conditions prior to the start of the system failure and described the conditions for the hours preceding the cascading failure of a large part of the Eastern Interconnect. Part II covers the actual cascading failure and describes how it spread, and finally stopped.

I. Background

The August 14, 2003 blackout affected the northeastern portion of the Eastern Interconnection, covering portions of three NERC regions. The blackout affected electric systems in northern Ohio, eastern Michigan, northern Pennsylvania and New Jersey, much of New York and Ontario. To a lesser extent, Massachusetts, Connecticut, Vermont, and Québec were impacted. The areas affected by the August 14 blackout are shown in Figure 1.

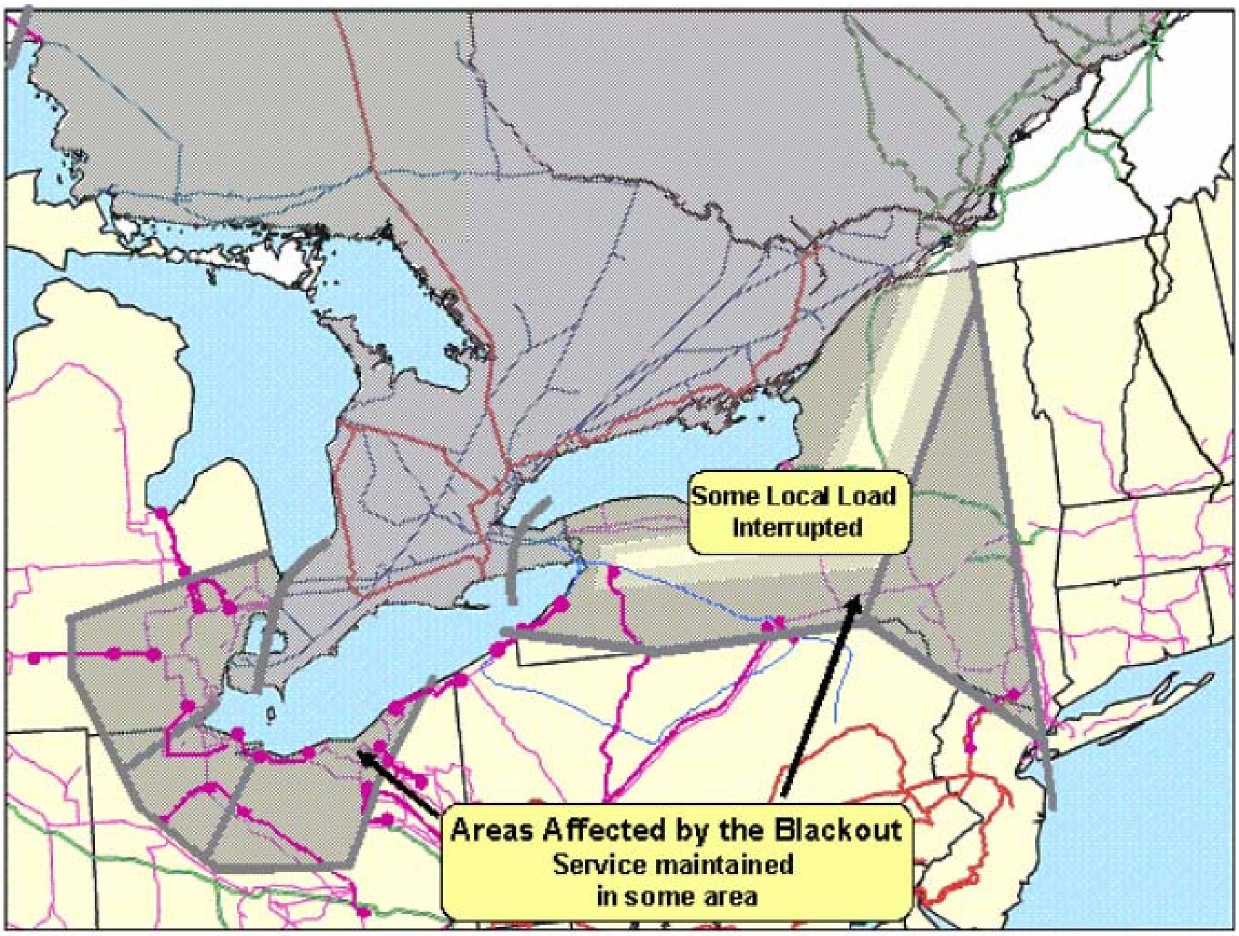

Figure 1 — Area Affected by the Blackout

Part I of this series described how uncorrected problems in northern Ohio developed to 16:05:57; the last point at which a cascade of line trips could have been averted. Part II details the sequence of events in the cascade, how and why it spread, and how it stopped in each geographic area.

The cascade spread beyond Ohio and caused a widespread blackout for three principal reasons.

1. The loss of the Sammis-Star line in Ohio, following the loss of other transmission lines and weak voltages within Ohio, triggered many subsequent line trips.
2. Many of the key lines that tripped between 16:05:57 and 16:10:38 operated on impedance relays, which responded to overloads rather than faults on the protected facilities. The speed at which they tripped accelerated the spread of the cascade beyond the Cleveland-Akron area.
3. The evidence indicates that the relay protection settings for the transmission lines, generators, and under-frequency load shedding in the Northeast may not be sufficient to reduce the likelihood and consequences of a cascade, nor were they intended to do so. These issues are discussed in depth below.

II. How the Cascade Evolved

A series of line outages in northeastern Ohio starting at 15:05 caused heavy loadings on parallel circuits, leading to the trip and lock-out of the Sammis-Star line at 16:05:57. This was the event that triggered a cascade of line outages on the high voltage system, causing electrical fluctuations and generator trips such that within seven minutes the blackout rippled from the Cleveland-Akron area across much of the northeastern United States and Canada. By 16:13, more than 508 generating units at 265 power plants had been lost, and tens of millions of people in the United States and Canada were without electric power.

The collapse of the FE transmission system induced unplanned shifts of power across the region. Shortly before the collapse, large - but normal - electricity flows were moving through the FE system from generators in the south and west to load centers in northern Ohio, eastern Michigan, and Ontario. Once the 345-kV and 138-kV system outages occurred in the Cleveland-Akron area, power that was flowing into that area over those lines shifted onto lines to the west and the east. The rapid increase in loading caused a series of lines within northern Ohio to trip on impedance relays. A “rippling” effect occurred as the transmission outages propagated west across Ohio into Michigan. The initial propagation of the cascade can best be described as a series of line trips caused by sudden, steady state power shifts that overloaded other lines — a “domino” effect.

The line trips progressed westward across Ohio, then northward into Michigan, separating western and eastern Michigan, causing a 500 MW power reversal within Michigan toward Cleveland. Many of these line trips were caused by impedance relay actions that accelerated the speed of the line trips. With paths cut from the west, a massive power surge flowed from PJM into New York and Ontario in a counter-clockwise flow around Lake Erie to serve the load still connected in eastern Michigan and northern Ohio. Transient instability began after 16:10:38, and large power swings occurred. First, a power surge of 3,700 MW flowed into Michigan across the Canadian border. Then the flow reversed by 5,800 MW within one second and peaked at 2,100 MW from Michigan to Canada. Relays on the lines between PJM and New York saw massive power swings and tripped those lines. Ontario’s east-west tie line also tripped, leaving northwestern Ontario connected to Manitoba and Minnesota.

The entire northeastern United States and eastern Ontario then became a large electrical island separated from the rest of the Eastern Interconnection. The major transmission split initially occurred along the long transmission lines across the Pennsylvania border to New York, and then proceeded into northeastern New Jersey. The resulting large electrical island, which had been importing power prior to the cascade, quickly became unstable after the massive transient swings and system separation. There was not sufficient generation on-line within the island to meet electricity demand. Systems to the south and west of the split, such as PJM, AEP, and others further away, remained intact and were mostly unaffected by the outage. Once the Northeast split from the rest of the Eastern Interconnection, the cascade was isolated to that portion of the Interconnection.

In the final phase, after 16:10:46, the large electrical island in the northeast had less generation than load, and was unstable with large power surges and swings in frequency and voltage. As a result, many lines and generators across the disturbance area tripped, breaking the area into several electrical islands.

Generation and load within most of the smaller islands were unbalanced, leading to further tripping of lines and generating units until equilibrium was established in each island. Although much of the disturbance area was fully blacked out in this process, some islands were able to reach equilibrium between generation and load without a total loss of service. For example, the island consisting of most of New England and the Maritime provinces stabilized, and generation and load returned to balance.

Another island consisted of load in western New York and a small portion of Ontario, supported by some New York generation, the large Beck and Saunders plants in Ontario, and the 765-kV interconnection to Québec. These two large islands survived but other areas with large load centers collapsed into a blackout condition.

Northern Ohio and South-Central Michigan

After the loss of Sammis-Star and the underlying 138-kV system, there were no large capacity transmission lines left from the south to support the significant amount of load in northern Ohio This overloaded the transmission paths west and northwest into Michigan, causing a sequential loss of lines and power plants.

The key events in this phase of the cascade were:

- 16:05:57: Sammis-Star 345-kV line tripped by zone 3 impedance relay
- 16:08:59: Galion-Ohio Central-Muskingum 345-kV line tripped
- 16:09:06: East Lima-Fostoria Central 345-kV line tripped on zone 3 impedance relay, causing a ripple of power swings through New York and Ontario into Michigan
- 16:09:08 to 16:10:27: Several power plants were lost, totaling 937 MW

Sammis-Star 345-kV Trip: 16:05:57 EDT

Sammis-Star did not trip due to a short circuit to ground (as did the prior 345-kV lines that tripped). Sammis-Star tripped due to protective impedance relays that measured low apparent impedance. There was no fault and no major power swing at the time of the trip; rather, high flows at 130 percent of the line's emergency rating, together with depressed voltages, caused the overload to appear to the protective relays as a remote fault on the system. In effect, the relay could no longer differentiate between a remote three-phase fault and conditions of high loading and low voltage. Moreover, the reactive flows (VARS) on the line were almost ten times higher than they had been earlier in the day because of the degrading conditions in the Cleveland-Akron area. The relay operated as designed.

The Sammis-Star trip completely severed the 345-kV path into northern Ohio from southeastern Ohio, triggering a new, fast-paced sequence of 345-kV transmission line trips in which each line trip placed a greater flow burden on those lines remaining in service. These line outages left only three paths for power to flow into western Ohio: (1) from northwestern Pennsylvania to northern Ohio around the south shore of Lake Erie, (2) from southwestern Ohio toward northeastern Ohio, and (3) from eastern Michigan and Ontario. The line interruptions substantially weakened northeast Ohio as a source of power to eastern Michigan, making the Detroit area more reliant on 345-kV lines west and northwest of Detroit, and from northwestern Ohio to eastern Michigan.

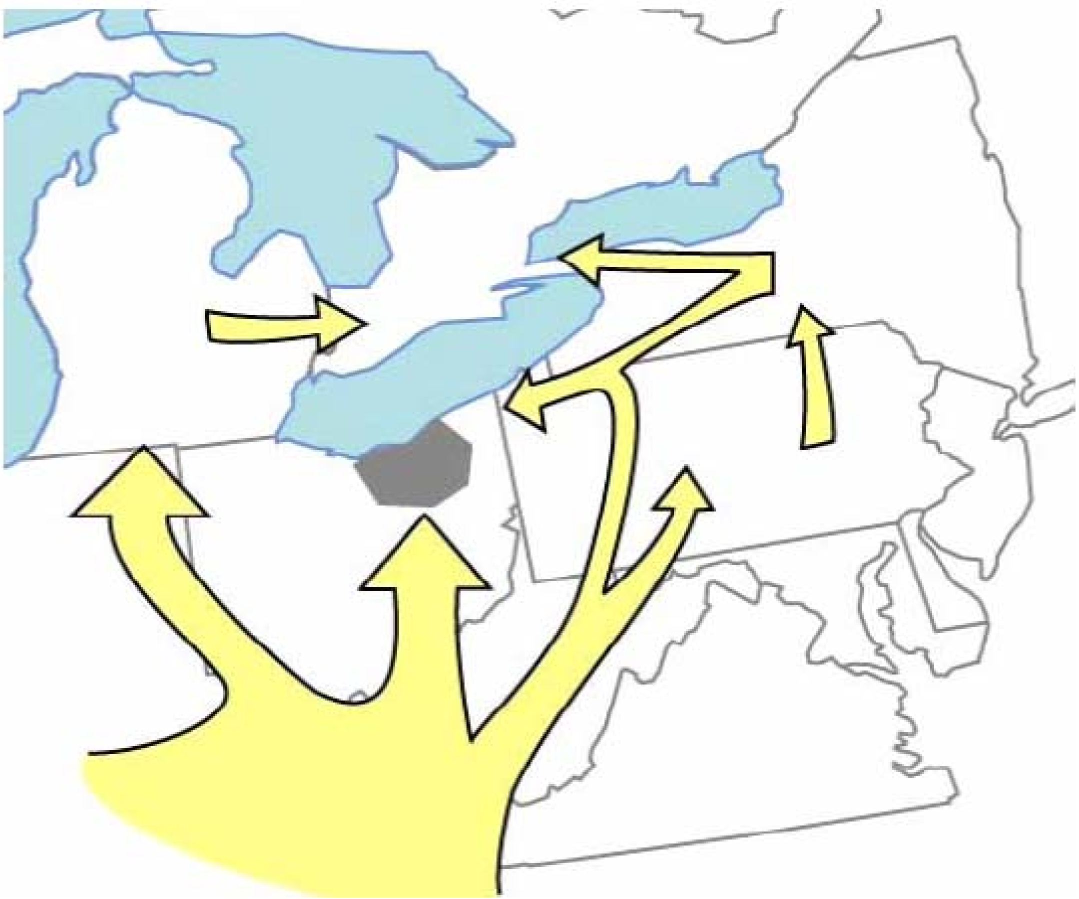

Figure 2 - Power Flows at 16:05:57, Prior to the Sammis-Star Trip

Soon after the Sammis-Star trip, four of the five 48 MW Handsome Lake combustion turbines in western Pennsylvania tripped off-line. These units are connected to the 345-kV system by the Homer City-Wayne 345-kV line, and were operating that day as synchronous condensers to participate in PJM's spinning reserve market (not to provide voltage support). When Sammis-Star tripped and increased loadings on the local transmission system, the Handsome Lake units were close enough electrically to sense the impact and tripped off-line at 16:07:00 on under-voltage relay protection.

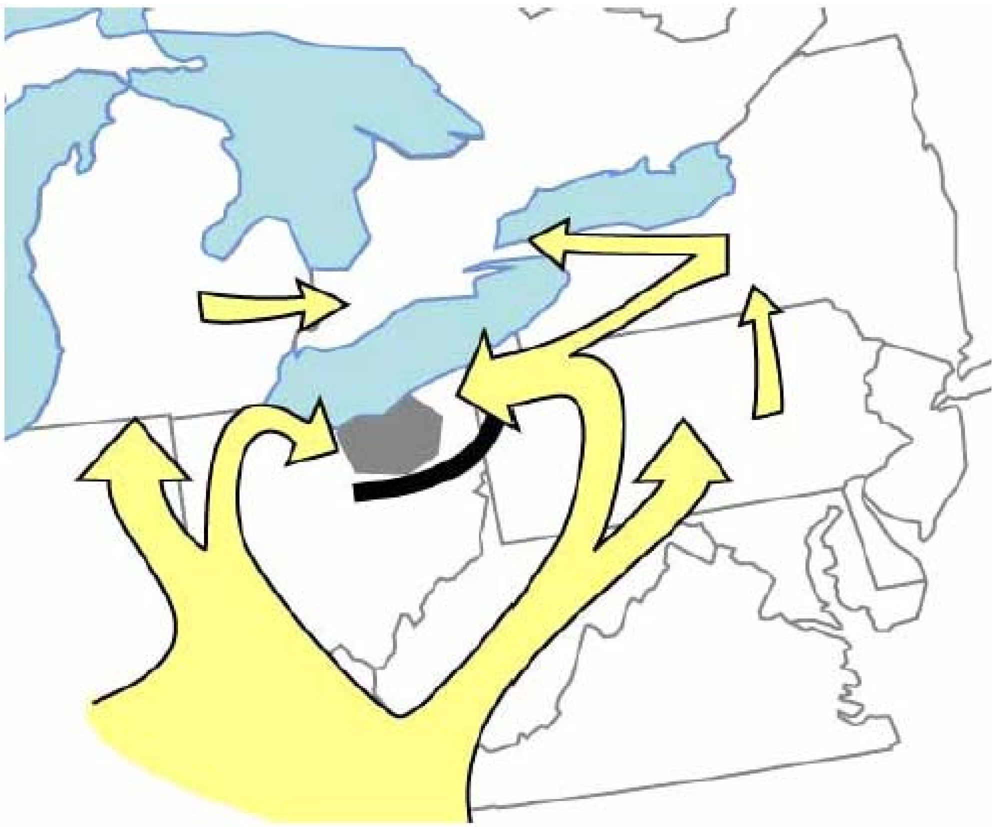

Figure 2 - Power Flows at 16:05:58, After the Sammis-Star Trip

During the period between the Sammis-Star trip and the trip of East Lima-Fostoria 345-kV line at 16:09:06.3, the system was still in a steady-state condition. Although one line after another was overloading and tripping within Ohio, this was happening slowly enough under relatively stable conditions that the system could readjust; after each line loss, power flows would redistribute across the remaining lines. The shift from 150 MW of imports to 200 MW of exports from the MECS system into FE at 16:05:57 after the loss of Sammis-Star, after which this held steady until 16:08:59, when the loss of East Lima-Fostoria Central cut the main energy path from the south and west into Cleveland and Toledo. Loss of this path was significant, causing flow from MECS into FE to jump from 200 MW up to 2,300 MW, where it swung dynamically before stabilizing.

Line Trips Westward across Ohio and Generator Trips in Michigan and Ohio:

The key events from 16:08:59 to 16:10:27 EDT in the cascade are:

- 16:08:59: Galion-Ohio Central-Muskingum 345-kV line tripped
- 16:09:06: East Lima-Fostoria Central 345-kV line tripped, causing a large power swing from Pennsylvania and New York through Ontario to Michigan

The Muskingum-Ohio Central-Galion line tripped first at Muskingum at 16:08:58.5 on a phase-to-ground fault. The line reclosed and tripped again at 16:08:58.6 at Ohio Central. The line reclosed a second time and tripped again at Muskingum on a zone 3 relay. Finally, the line tripped and locked open at Galion on a low magnitude B Phase ground fault. After the Muskingum-Ohio Central-Galion line outage and numerous 138-kV line trips in central Ohio, the East Lima-Fostoria Central line tripped at 16:09:06 on zone 3 relay operation due to high current and low voltage (80 percent). Modeling indicates that if automatic under-voltage load-shedding had been in place in northeastern and central Ohio, it might have been triggered at or before this point and dropped enough load to reduce or eliminate the subsequent line overloads that spread the cascade.

The tripping of the Galion-Ohio Central-Muskingum and East Lima-Fostoria Central transmission lines removed the transmission paths from southern and western Ohio into northern Ohio and eastern Michigan. Northern Ohio was connected to eastern Michigan by only three 345-kV transmission lines near the southwestern bend of Lake Erie. Thus, the combined northern Ohio and eastern Michigan load centers were left connected to the rest of the grid only by: (1) transmission lines eastward from northeastern Ohio to northwestern Pennsylvania along the southern shore of Lake Erie, and (2) westward by lines west and northwest of Detroit, Michigan, and from Michigan into Ontario (See Figure 4).

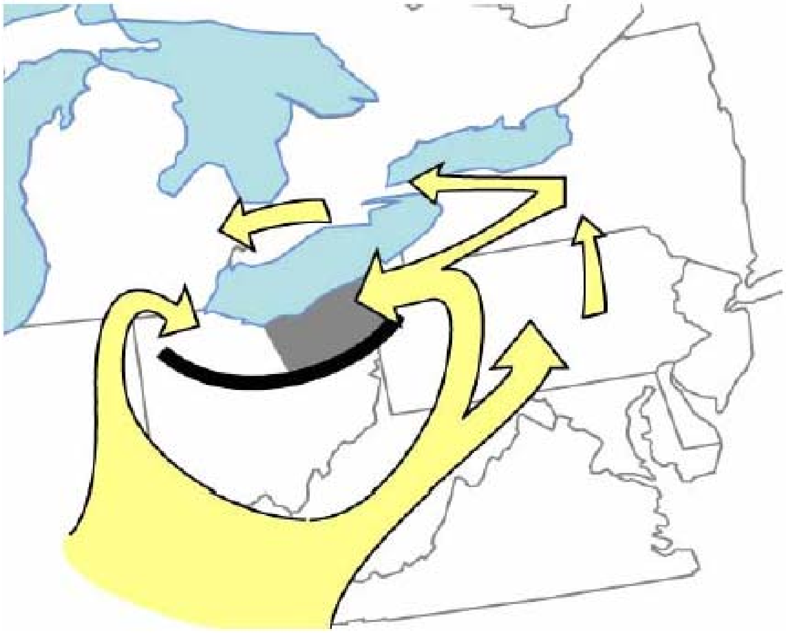

Figure 4 - Power Flows at 16:09:25

Although the blackout of August 14 has been labeled by some as a voltage collapse, it was not a voltage collapse as that term has been traditionally used by power system engineers. Voltage collapse occurs when an increase in load or loss of generation or transmission facilities causes voltage to drop, which causes a further reduction in reactive power from capacitors and line charging, and still further voltage reductions. If the declines continue, these voltage reductions cause additional elements to trip, leading to further reduction in voltage and loss of load. The result is a progressive and uncontrollable decline in voltage because the power system is unable to provide the reactive power required to supply the reactive power demand. This did not occur on August 14. While the Cleveland-Akron area was short of reactive power reserves, there was sufficient reactive supply to meet the reactive power demand in the area and maintain stable albeit depressed 345-kV voltage for the outage conditions experienced from 13:31 to 15:32. This included the first forced outage at 13:31 (Eastlake 5 trip) to the third contingency at 15:32 (Hanna-Juniper trip). Only after the fourth contingency, the lockout of South Canton-Star at 15:42, did the 345-kV voltage drop below 90 percent at the Star substation.

The cascade progressed beyond Ohio because of large line currents with depressed voltages, dynamic power swings when the East Lima-Fostoria Central line trip separated southern Ohio from northern Ohio, and the resulting transient instability after northern Ohio and eastern Michigan were isolated onto the Canadian system.

The voltage levels remained stable across the Niagara area until about 16:10:30, despite significant power fluctuations. In the cascade that followed, the voltage instability was a companion to, not a driver of, the angular instability that tripped generators and lines. A high-speed recording of 345-kV flows at Niagara Falls taken by the Hydro One recorders, showed the impact of the East Lima-Fostoria Central and the New York -to-Ontario power swing, which continued to oscillate for more than ten seconds. When Sammis-Star tripped, the system experienced oscillations that quickly damped out and rebalanced. But East Lima-Fostoria triggered significantly greater oscillations that worsened in magnitude for several cycles, and then dampened more slowly but continued to oscillate until the Argenta-Battle Creek trip 90 seconds later. Voltages also began to decline at that time.

After the East Lima-Fostoria Central trip, power flows increased dramatically and quickly on the lines into and across southern Michigan. Although power had initially been flowing northeast out of Michigan into Ontario, that flow suddenly reversed and approximately 500 to 700 MW of power flowed southwest out of Ontario through Michigan to serve the load of Cleveland and Toledo. This flow was fed by 700 MW pulled out of PJM through New York on its 345-kV network. This was the first of several inter-area power and frequency events that occurred over the next two minutes. This was the system's response to the loss of the northwestern Ohio transmission paths, and the stress that the Cleveland, Toledo, and Detroit loads put onto the surviving lines and local generators.

The very low voltages on the northern Ohio transmission system made it difficult for the generation in the Cleveland and Lake Erie area to remain synchronous with southeast Michigan. Over the next two minutes, generators in this area shut down after reaching a point of no recovery as the stress level across the remaining ties became excessive.

Beginning at 16:09:05, power flows jumped simultaneously across all three interfaces; but when the first power surge peaked at 16:09:09, the change in flow was highest on the PJM interface and lowest on the New England interface. Power flows increased significantly on the PJM-New York and New York-Ontario interfaces because of the redistribution of flow around Lake Erie to serve the loads in northern Ohio and eastern Michigan. The New England and Maritimes systems maintained the same generation-to-load balance and did not carry the redistributed flows because they were not in the direct path of the flows. Therefore, the New England-New York interface flows showed little response.

Before this first major power swing on the Michigan/Ontario interface, power flows in the NPCC Region (Québec, Ontario and the Maritimes, New England, and New York) were typical for the summer period and well within acceptable limits. Up until this time, transmission and generation facilities were in a secure state across the NPCC region.

Loss of Generation

The following generation was lost from 16:09:08 to 16:10:27:

- 16:09:08: Michigan Cogeneration Venture (MCV) plant run back of 300 MW

- 16:09:15: Avon Lake 7 unit tripped (82 MW)
- 16:09:17: Burger 3, 4, and 5 units tripped (355 MW total)
- 16:09:23 to 30: Kinder Morgan units 3, 6, and 7 tripped (209 MW total)

The MCV plant in central Michigan experienced a 300 MW run-back. The Avon Lake 7 unit tripped due to the loss of the voltage regulator. The Burger units tripped after the 138-kV lines from the Burger 138-kV generating substation bus to substations in Ohio tripped from high reactive power flow due to the low voltages in the Cleveland area. Three units at the Kinder Morgan generating station in south-central Michigan tripped due to a transformer fault and over-excitation.

Power flows into Michigan from Indiana increased to serve loads in eastern Michigan and northern Ohio (still connected to the grid through northwest Ohio and Michigan) and voltages dropped from the imbalance between high loads and limited transmission and generation capability.

III. High Speed Cascade

Between 16:10:36 and 16:13, a period of less than a minute and a half, a chain reaction of thousands of events occurred on the grid, driven by physics and automatic equipment operations. When it was over, much of the Northeast was in the dark.

Transmission and Generation Trips in Michigan:
From16:10:36 to 16:10:37 EDT the following key events occurred as the cascade propagated from Ohio and sliced through Michigan:

- 16:10:36.2: Argenta-Battle Creek 345-kV line tripped
- 16:10:36.3: Argenta-Tompkins 345-kV line tripped
- 16:10:36.8: Battle Creek-Oneida 345-kV line tripped
- 16:10:37: Sumpter Units 1, 2, 3, and 4 units tripped on under-voltage (300 MW near Detroit)
- 16:10:37.5: MCV Plant output dropped from 944 MW to 109 MW on over-current protection

Together, the above line outages interrupted the west-to-east transmission paths into the Detroit area from south-central Michigan. The Sumpter generating units tripped in response to under-voltage on the system. Michigan lines west of Detroit then began to trip.

The Argenta-Battle Creek relay first opened the line at 16:10:36.230. The line reclosed automatically at 16:10:37, then tripped again. This line connects major generators — including the Cook and Palisades nuclear plants and the Campbell fossil plant — to the Eastern MECS system. This line is designed with auto-reclose breakers at each end of the line, which do an automatic high-speed reclose as soon as they open to restore the line to service with no interruptions. Since the majority of faults on the North American grid are temporary, automatic reclosing can enhance stability and system reliability. However, situations can occur where the power systems behind the two ends of the line could go out of phase during the high-speed reclose period (typically less than 30 cycles, or one half second, to allow the air to de-ionize after the trip to prevent arc re-ignition). To address this and protect generators from the harm that an out-of-synchronism reconnect could cause, it is worth studying whether a synchro-check relay is needed to reclose only when the two ends of a line are within a certain voltage and phase angle tolerance.

No such protection was installed at Argenta-Battle Creek. When the line reclosed, there was a 70 degree difference in phase across the circuit breaker reclosing the line. There is no evidence that the reclose harmed the local generators. Power flows following the trip of the central Michigan lines are shown in Figure 5.

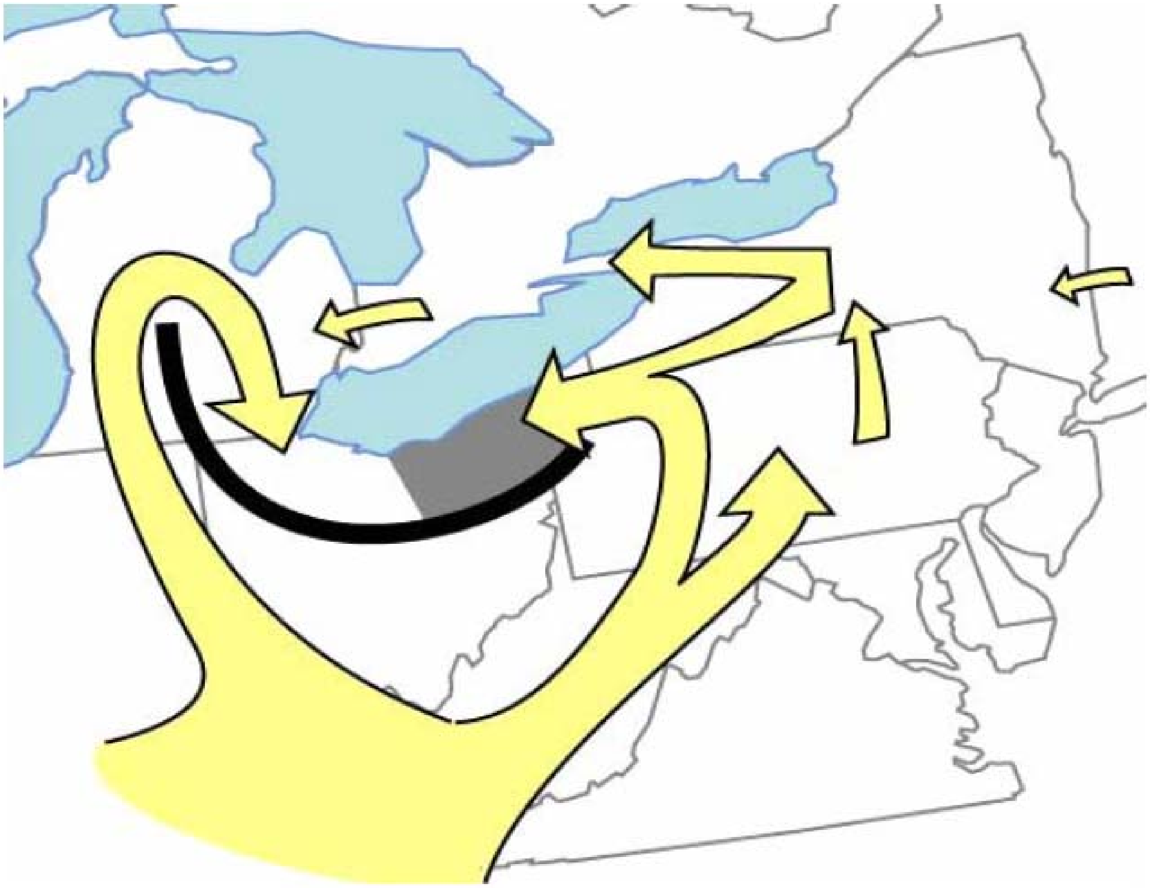

Figure 5 - Power Flows at 16:10:37

Western and Eastern Michigan Separate:

From 16:10:37 to 16:10:38 EDT the following key events occurred at 16:10:37–38:

- 16:10:38.2: Hampton-Pontiac 345-kV line tripped
- 16:10:38.4: Thetford-Jewell 345-kV line tripped

After the Argenta lines tripped, the phase angle between eastern and western Michigan significantly increased. Hampton-Pontiac and Thetford-Jewell were the only lines connecting Detroit to the rest of the grid to the north and west. When these lines tripped out of service, it left the loads in Detroit, Toledo, Cleveland, and their surrounding areas served only by local generation and the lines north of Lake Erie connecting Detroit east to Ontario and the lines south of Lake Erie from Cleveland east to northwestern Pennsylvania. These trips completed the separation of the high voltage transmission system between eastern and western Michigan.

The west-to-east Michigan separation (culminating with the Thetford-Jewell trip), combined a fraction of a second later with the trip of the Erie West-Ashtabula-Perry 345-kV line connecting Ohio and Pennsylvania, was the trigger for a sudden 3,700 MW power surge from Ontario into Michigan. When Thetford-Jewell tripped, power that had been flowing into Michigan and Ohio from western Michigan, western Ohio, and Indiana was cut off. The nearby Ontario recorders saw a pronounced impact as flows into Detroit readjusted to flow in from Ontario instead.

On the boundary of northeastern Ohio and northwestern Pennsylvania, the Erie West-Ashtabula-Perry line was the last 345-kV link to the east for northern Ohio loads. When that line severed, all the power that moments before had flowed across Michigan and Ohio paths was now diverted in a counterclockwise loop around Lake Erie through the single path left in eastern Michigan, pulling power out of Ontario, New York, and PJM.

Large Counter-clockwise Power Surge around Lake Erie:
The following key events occurred at 16:10:38:

- 16:10:38.2: Hampton-Pontiac 345-kV line tripped
- 16:10:38.4: Thetford-Jewell 345-kV line tripped
- 16:10:38.6: Erie West-Ashtabula-Perry 345-kV line tripped at Perry
- 16:10:38.6: Large power surge to serve loads in eastern Michigan and northern Ohio swept across Pennsylvania, New Jersey, and New York through Ontario into Michigan.

Perry-Ashtabula was the last 345-kV line connecting northern Ohio to the east along the southern shore of Lake Erie. This line tripped at the Perry substation on a zone 3 relay operation and separated the northern Ohio 345-kV transmission system from Pennsylvania and all 345-kV connections. After this trip, the load centers in eastern Michigan and northern Ohio (Detroit, Cleveland, and Akron) remained connected to the rest of the Eastern Interconnection only to the north of Lake Erie at the interface between the Michigan and Ontario systems. Eastern Michigan and northern Ohio now had little internal generation left and voltage was declining. The frequency in the Cleveland area dropped rapidly, and between 16:10:39 and 16:10:50, under frequency load shedding in the Cleveland area interrupted about 1,750 MW of load. However, the load shedding was not enough to reach a balance with local generation and arrest the frequency decline. The still-heavy loads in Detroit and Cleveland drew power over the only major transmission path remaining: the lines from eastern Michigan east into Ontario.

At 16:10:38.6, after the 345-kV transmission paths in Michigan and Ohio tripped, the power that had been flowing at modest levels into Michigan from Ontario suddenly jumped in magnitude. While flows from Ontario into Michigan had been in the 250 to 350 MW range since 16:10:09.06, with this new surge the flows peaked at 3,700 MW at 16:10:39. Electricity moved along a giant loop from the rest of the Eastern Interconnection through Pennsylvania and into New York and Ontario, and then into Michigan via the remaining transmission path to serve the combined loads of Cleveland, Toledo, and Detroit. This sudden large change in power flows lowered voltages and increased current levels on the transmission lines along the Pennsylvania-New York transmission interface.

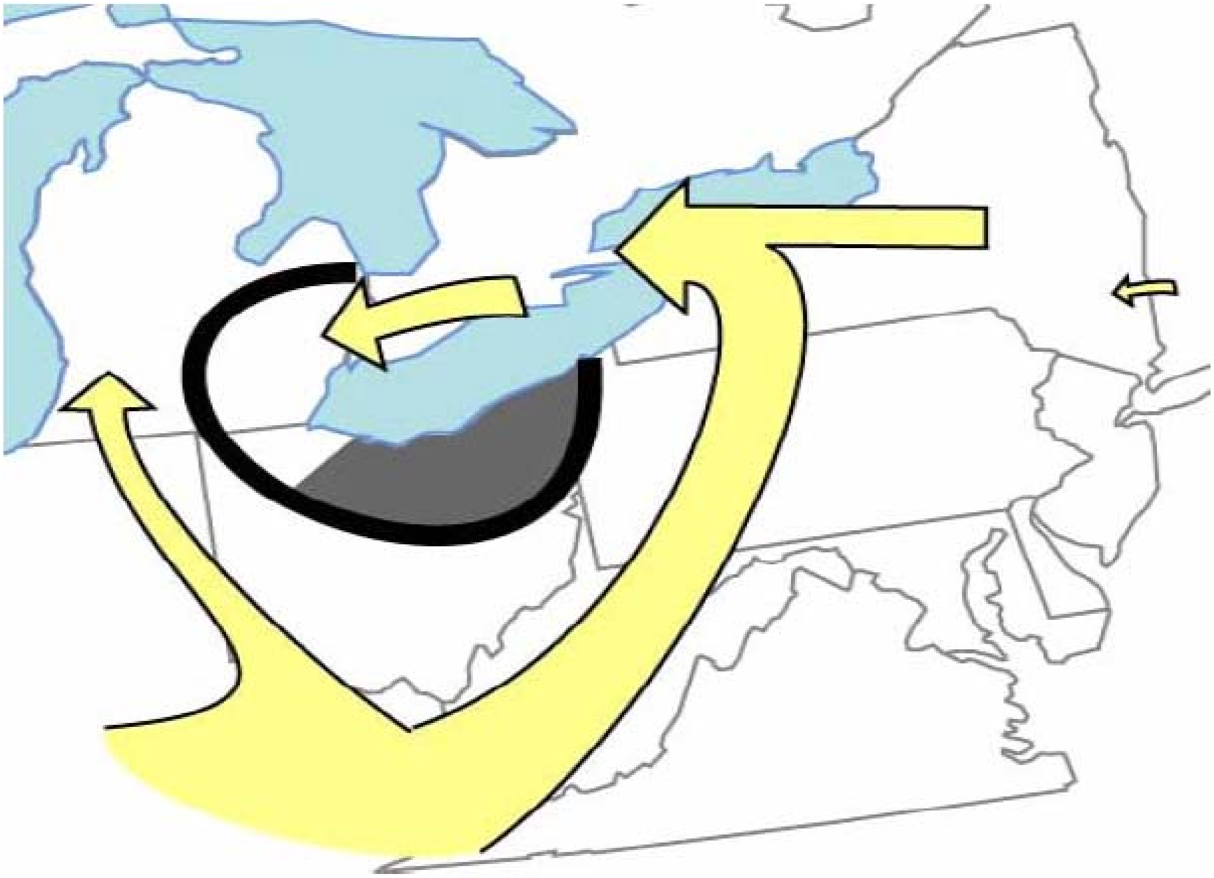

Figure 6 - Power Flows at 16:10:39

This power surge was of such a large magnitude that frequency was not the same across the Eastern Interconnection. The power swing resulted in a rapid rate of voltage decay. Flows into Detroit exceeded 3,700 MW and 1,500 MVAR; the power surge was draining real power out of the northeast, causing voltages in Ontario and New York to drop. At the same time, local voltages in the Detroit area were plummeting because Detroit had already lost 500 MW of local generation. The electric system in the Detroit area would soon lose synchronism and black out (as evidenced by the rapid power oscillations decaying after 16:10:43).

Just before the Argenta-Battle Creek trip, when Michigan separated west-to-east at 16:10:37, almost all of the generators in the Eastern Interconnection were operating in synchronism with the overall grid frequency of 60 Hertz, but when the large swing started, those machines began to swing dynamically. After the 345-kV line trip at 16:10:38, the Northeast entered a period of transient instability and loss of generator synchronicity. Between 16:10:38 and 16:10:41, the power swings caused a sudden localized increase in system frequency, hitting 60.7 Hz at Lambton and 60.4 Hz at Niagara.

Because the demand for power in Michigan, Ohio, and Ontario was drawing on lines through New York and Pennsylvania, heavy power flows were moving northward from New Jersey over the New York tie lines to meet those power demands, exacerbating the power swing. Figure 6 shows actual net line flows summed across the interfaces between the main regions affected by these swings: Ontario into Michigan, New York into Ontario, New York into New England, and PJM into New York. This shows that the power swings did not move in unison across every interface at every moment, but varied in magnitude and direction. This occurred for two reasons. First, the availability of lines across each interface varied over time, as did the amount of load that drew upon each interface, so net flows across each interface were not facing consistent demand with consistent capability as the cascade progressed. Second, the speed and magnitude of the swing was moderated by the inertia, reactive power capabilities, loading conditions, and locations of the generators across the entire region.

Because the loads of Cleveland, Toledo, and Detroit (less the load already blacked out) were now served through Michigan and Ontario, this forced a large shift in power flows to meet that demand. As noted above, flows from Ontario into Michigan increased from 1,000 MW to a peak of 3,700 MW shortly after the start of the swing, while flows from PJM into New York were close behind (Figure 7). But within one second after the peak of the swing, at 16:10:40, flows reversed and flowed back from Michigan into Ontario at the same time that frequency at the interface dropped. The large load and imports into northern Ohio were losing synchronism with southeastern Michigan. Flows that had been westbound across the Ontario-Michigan interface by more than 3,700 MW at 16:10:38.8 reversed to 2,100 MW eastbound by 16:10:40, and then returned westbound starting at 16:10:40.5.

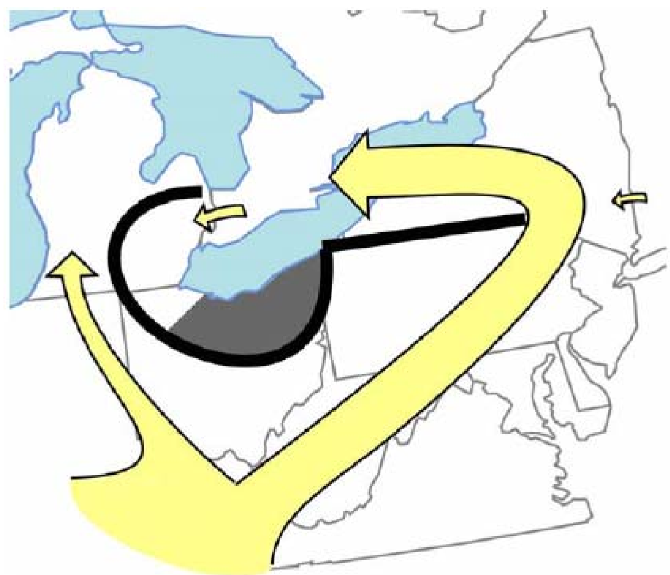

Figure 7 - Power Flows at 16:10:40

Two 345-kV lines tripped because of zone 1 impedance relay action along the border between PJM and the NYISO due to the transient overloads and depressed voltage. After the separation from PJM, the dynamic surges also drew power from New England and the Maritimes. The combination of the power surge and frequency rise caused 380 MW of pre-selected Maritimes generation to trip off-line due to the operation of the New Brunswick Power “Loss of Line 3001” Special Protection System. Although this system was designed to respond to failures of the 345-kV link between the Maritimes and New England, it operated in response to the effects of the power surge. The link remained intact during the event.

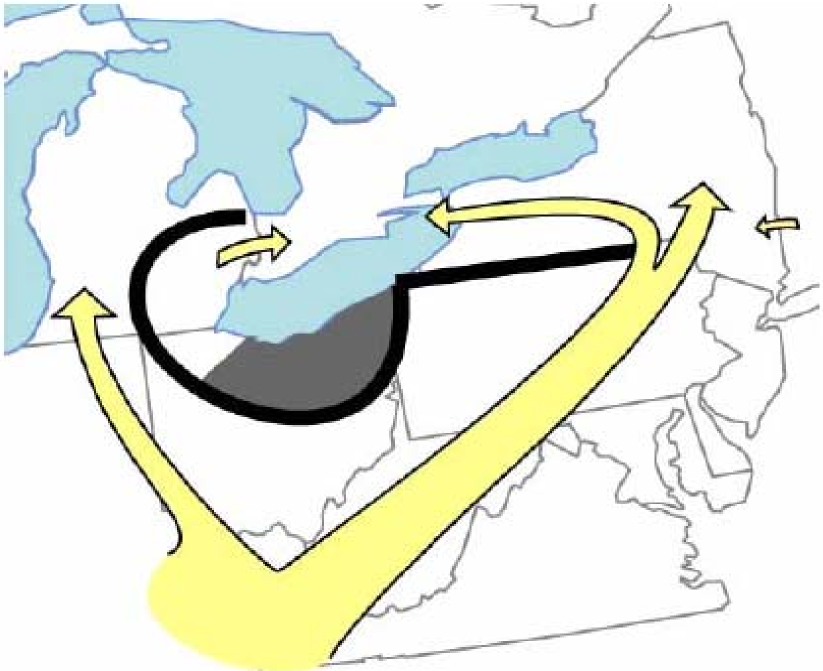

Figure 8 - Power Flows at 16:10:41

Northern Ohio and Eastern Michigan Systems Degraded Further:
The following events occurred in northern Ohio and eastern Michigan over a period of seven seconds from 16:10:39 to 16:10:46:

Line trips in Ohio and eastern Michigan:

- 16:10:39.5: Bayshore-Monroe 345-kV line
- 16:10:39.6: Allen Junction-Majestic-Monroe 345-kV line
- 16:10:40.0: Majestic-Lemoyne 345-kV line
- Majestic 345-kV Substation: one terminal opened sequentially on all 345-kV lines
- 16:10:41.8: Fostoria Central-Galion 345-kV line
- 16:10:41.911: Beaver-Davis Besse 345-kV line

Under-frequency load shedding in Ohio:

- FirstEnergy shed 1,754 MVA load
- AEP shed 133 MVA load

Six power plants, for a total of 3,097 MW of generation, tripped off-line in Ohio:

- 16:10:42: Bay Shore Units 1–4 (551 MW near Toledo) tripped on over-excitation
- 16:10:40: Lakeshore unit 18 (156 MW, near Cleveland) tripped on under frequency
- 16:10:41.7: Eastlake 1, 2, and 3 units (304 MW total, near Cleveland) tripped on under frequency

- 16:10:41.7: Avon Lake unit 9 (580 MW, near Cleveland) tripped on under frequency
- 16:10:41.7: Perry 1 nuclear unit (1,223 MW, near Cleveland) tripped on under frequency
- 16:10:42: Ashtabula unit 5 (184 MW, near Cleveland) tripped on under frequency

Five power plants producing 1,630 MW tripped off-line near Detroit:

- 16:10:42: Greenwood unit 1 tripped (253 MW) on low voltage, high current
- 16:10:41: Belle River unit 1 tripped (637 MW) on out-of-step
- 16:10:41: St. Clair unit 7 tripped (221 MW, DTE unit) on high voltage
- 16:10:42: Trenton Channel units 7A, 8, and 9 tripped (648 MW)
- 16:10:43: West Lorain units (296 MW) tripped on under-voltage

In northern Ohio, the trips of the Bay Shore-Monroe, Majestic-Lemoyne, Allen Junction-Majestic-Monroe 345-kV lines, and the Ashtabula 345/138-kV transformer cut off Toledo and Cleveland from the north, turning that area into an electrical island. After these 345-kV line trips, the high power imports from southeastern Michigan into Ohio suddenly stopped at 16:10:40. Frequency in this island began to fall rapidly. This caused a series of power plants in the area to trip off-line due to the operation of under frequency relays, including the Bay Shore units. Cleveland area load was disconnected by automatic under frequency load shedding (approximately 1,300 MW), and another 434 MW of load was interrupted after the generation remaining within this transmission island was tripped by under frequency relays. This sudden load drop would contribute to the reverse power swing described previously. In its own island, portions of Toledo blacked out from automatic under frequency load shedding but most of the Toledo load was restored by automatic reclosing of lines such as the East Lima-Fostoria Central 345-kV line and several lines at the Majestic 345-kV substation.

The Perry nuclear plant is located in Ohio on Lake Erie, not far from the Pennsylvania border. The Perry plant was inside the decaying electrical island and tripped soon thereafter on under-frequency, as designed.

A number of other units near Cleveland tripped off-line by under frequency protection. Voltage in the island dropped, causing the Beaver-Davis Besse 345-kV line between Cleveland and Toledo to trip. This marked the end for Cleveland, which could not sustain itself as a separate island. However, by separating from Cleveland, Toledo was able to resynchronize with the rest of the eastern inter-connection once the phase angle across the open East Lima-Fostoria 345-kV line came back within its limits and re-closed.

The large power surge into Michigan, beginning at 16:10:38, occurred when Toledo and Cleveland were still connected to the grid through Detroit. After the Bayshore-Monroe line tripped at 16:10:39, Toledo and Cleveland separated into their own island, dropping a large amount of load off of the Detroit system.

This suddenly left Detroit with excess generation, much of which greatly accelerated in angle as the depressed voltage in Detroit (caused by the high demand in Cleveland) caused the Detroit units to begin to pull out of step with the rest of the grid. When voltage in Detroit returned to near-normal, the generators could not sufficiently decelerate to remain synchronous. This out-of-step condition is evident in Figure 9, which shows at least two sets of generator “pole slips” by plants in the Detroit area between 16:10:40 and 16:10:42. Several large units around Detroit: Belle River, St. Clair, Greenwood, Monroe, and Fermi Nuclear all tripped in response. After the Cleveland-Toledo island formed at 16:10:40, Detroit frequency spiked to almost 61.7 Hz before dropping, momentarily equalized between the Detroit and Ontario systems. But Detroit frequency then began to decay at 2 Hz/sec and the generators experienced under-speed conditions.

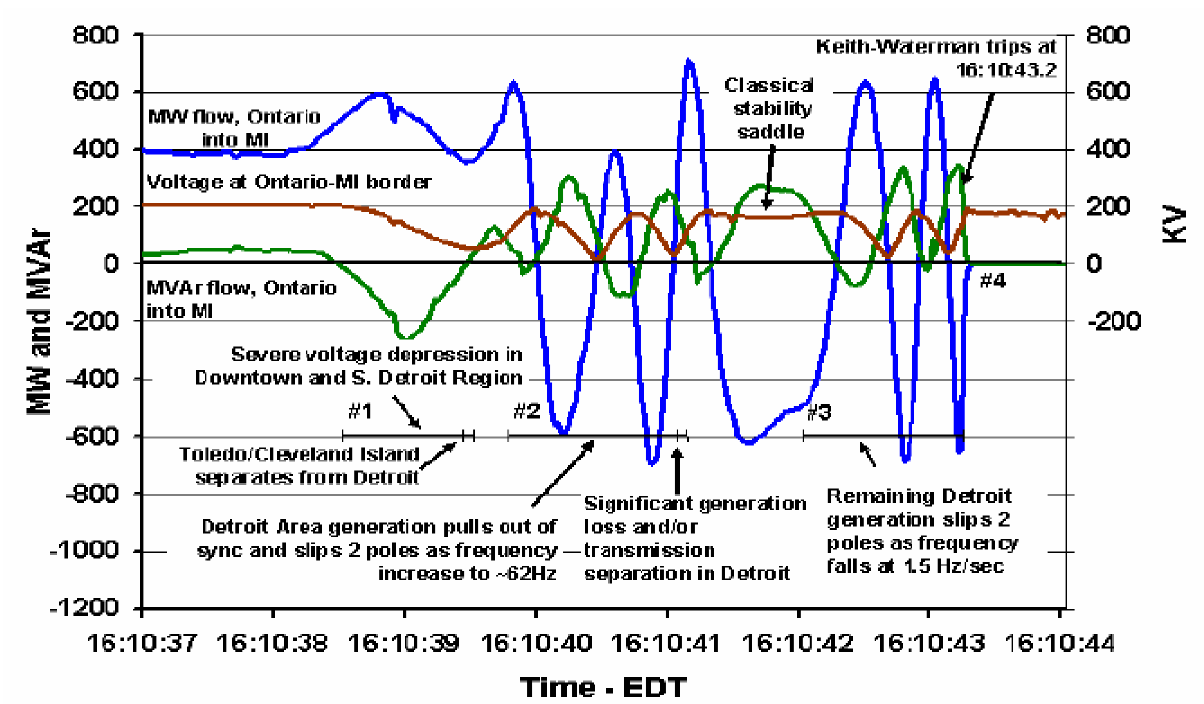

Figure 9 - Generators Under Stress in Detroit, as Seen From Keith PSDR

The power swing from the northeast through Ontario into Michigan and northern Ohio that began at 16:10:37, reversed and swung back around Lake Erie at 16:10:39. That return was caused by the combination of natural oscillation accelerated by major load losses, as the northern Ohio system disconnected from Michigan. It caused a power flow change of 5,800 MW, from 3,700 MW westbound to 2,100 eastbound across the Ontario-to-Michigan border between 16:10:39.5 and 16:10:40. Since the system was now fully dynamic, this large oscillation eastbound would lead naturally to a rebound, which began at 16:10:40 with an inflection point reflecting generation shifts between Michigan and Ontario and additional line losses in Michigan.

Western Pennsylvania-New York Separation:

The following events occurred over a five-second period from 16:10:39 to 16:10:44, beginning the separation of New York and Pennsylvania:

- 16:10:39: Homer City-Watercure Road 345-kV
- 16:10:39: Homer City-Stolle Road 345-kV
- 16:10:44: South Ripley-Erie East 230-kV, and South Ripley-Dunkirk 230-kV
- 16:10:44: East Towanda-Hillside 230-kV

Responding to the swing of power out of Michigan toward Ontario and into New York and PJM, zone 1relays on the 345-kV lines separated Pennsylvania from New York. Homer City-August Watercure (177 miles) and Homer City-Stolle Road (207 miles) are relatively long lines with high impedances. Zone 1 relays do not have timers, and therefore operate nearly instantly when a power swing enters the relay target circle. For normal length lines, zone 1 relays have smaller target circles because the relay is measuring less than the full length of the line, but for a long line the greater impedance enlarges the relay target circle and makes it more likely to be hit by the power swing. The Homer City-Watercure and Homer City-Stolle Road lines do not have zone 3 relays.

Given the length and impedance of these lines, it was highly likely that they would trip and separate in the face of such large power swings. Most of the other interfaces between regions have shorter ties. For instance, the ties between New York and Ontario and Ontario to Michigan are only about two miles long, so they are electrically very short and thus have much lower impedance and trip less easily than these long lines. A zone 1 relay target on a short line covers a small distance so a power swing is less likely to enter the relay target circle at all, averting a zone 1 trip.

At 16:10:44, (see Figure 10) the northern part of the Eastern Interconnection (including eastern Michigan) was connected to the rest of the Interconnection at only two locations: (1) in the east through the 500-kV and 230-kV ties between New York and northeastern New Jersey, and (2) in the west through the long and electrically fragile 230-kV transmission path connecting Ontario to Manitoba and Minnesota.

The separation of New York from Pennsylvania (leaving only the lines from New Jersey into New York connecting PJM to the northeast) helped to buffer PJM in part from these swings. Frequency was high in Ontario at that point, indicating that there was more generation than load, so much of this flow reversal never got past Ontario into New York.

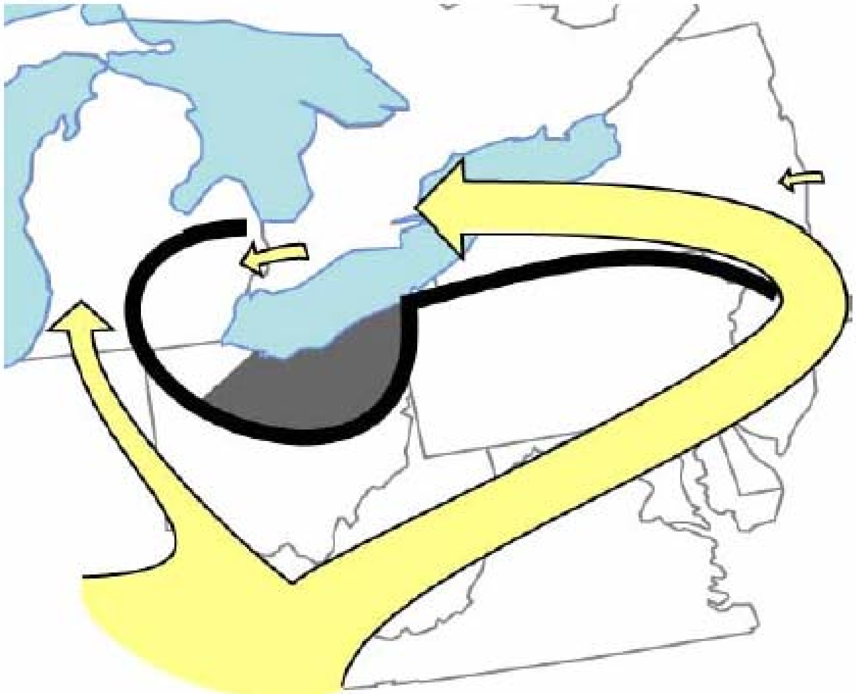

Figure 10 - Power Flows at 16:10:44

Final Separation of the Northeast from the Eastern Interconnection:

The following line trips between 16:10:43 to 16:10:45 resulted in the northeastern United States and eastern Canada becoming an electrical island completely separated from the rest of the Eastern Interconnection:

- 16:10:43: Keith-Waterman 230-kV line tripped
- 16:10:45: Wawa-Marathon 230-kV lines tripped
- 16:10:45: Branchburg-Ramapo 500-kV line tripped

At 16:10:43, eastern Michigan was still connected to Ontario, but the Keith-Waterman line that forms part of that interface disconnected due to apparent impedance. This put more power onto the remaining interface between Ontario and Michigan, but triggered sustained oscillations in both power flow and frequency along the remaining 230-kV line.

At 16:10:45, northwest Ontario separated from the rest of Ontario when the Wawa-Marathon 230-kV lines disconnected along the northern shore of Lake Superior, tripped by zone 1 distance relays at both ends. This separation left the loads in the far northwest portion of Ontario connected to the Manitoba and Minnesota systems, and protected them from the blackout.

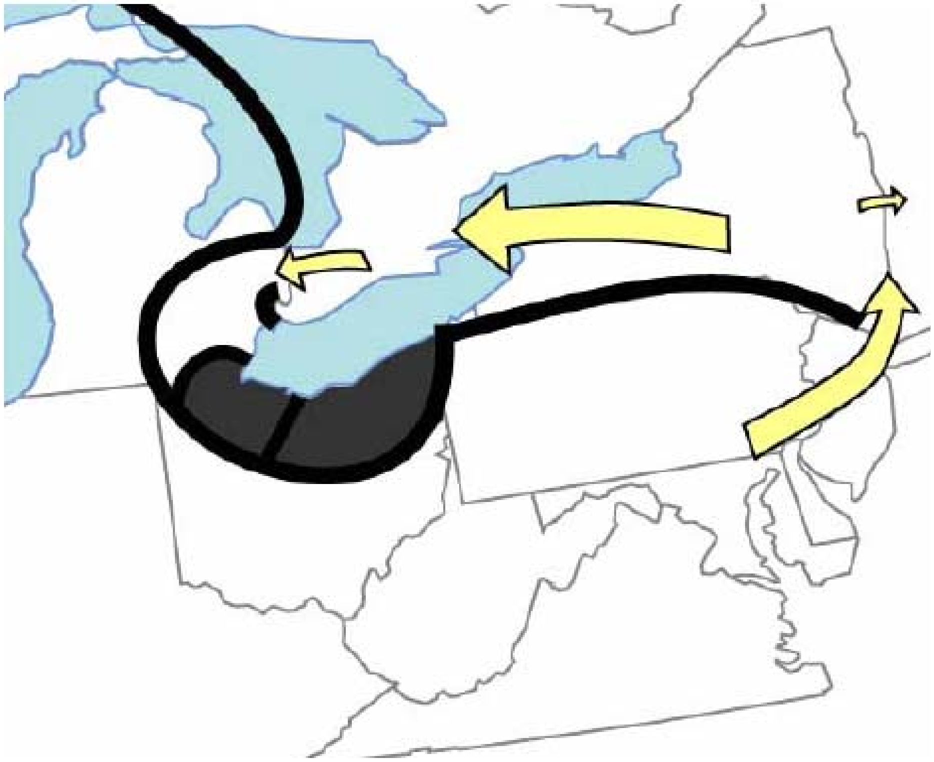

Figure 11 - Power Flows at 16:10:45

As shown in Figure 11, the 69-mile long Branchburg-Ramapo line and Ramapo transformer between New Jersey and New York was the last major transmission path remaining between the Eastern Interconnection and the area ultimately affected by the blackout. That line disconnected at 16:10:45, along with other underlying 230 and 138-kV lines in northeastern New Jersey.

Branchburg-Ramapo was carrying over 3,000 MVA and 4,500 amps with voltage at 79 percent before it tripped, either on a high-speed swing into zone 1 or on a direct transfer trip. The investigation team is still examining why the higher impedance 230-kV overhead lines tripped while the underground Hudson-Farragut 230-kV cables did not; the available data suggest that the lower impedance of underground cables made these less vulnerable to the electrical strain placed on the system.

This left the northeast portion of New Jersey connected to New York, while Pennsylvania and the rest of New Jersey remained connected to the rest of the Eastern Interconnection. Within northeastern New Jersey, the separation occurred along the 230-kV corridors, which are the main supply feeds into the northern New Jersey area (the two Roseland-Athenia circuits and the Linden-Bayway circuit). These circuits supply the large customer load in northern New Jersey and are a primary route for power transfers into New York City, so they are usually more highly loaded than other interfaces. These lines tripped west and south of the large customer loads in northeast New Jersey.

The separation of New York, Ontario, and New England from the rest of the Eastern Interconnection occurred due to natural breaks in the system and automatic relay operations, which performed exactly as designed. No human intervention occurred by any operators to affect this split.

IV. Electrical Islands Seek Equilibrium

At this point, the Eastern Interconnection was divided into two major sections. To the north and east of the separation point lay New York City, northern New Jersey, New York state, New England, the Canadian Maritimes provinces, eastern Michigan, the majority of Ontario, and the Québec system.

The rest of the Eastern Interconnection, to the south and west of the separation boundary, was not seriously affected by the blackout. Approximately 3,700 MW of excess generation in the main portion of the Eastern Interconnection that was on-line to export into the Northeast was now separated from the load it had been serving. This left the northeastern island with even less in-island generation on-line as it attempted to stabilize during the final phase of the cascade.

During the next three seconds, the islanded northern section of the Eastern Interconnection broke apart internally.

- New York-New England upstate transmission lines disconnected: 16:10:46 to 16:10:47
- New York transmission system split along Total East interface: 16:10:49
- The Ontario system just west of Niagara Falls and west of St. Lawrence separated from the western New York island: 16:10:50

A half minute later, two more separations occur:

- Southwestern Connecticut separates from New York City: 16:11:22
- Remaining transmission lines between Ontario and eastern Michigan separate: 16:11:57

By this point, most portions of the affected area were blacked out. This last phase of the cascade is principally about the search for balance between loads and generation in the various islands that have formed. The primary mechanism for reaching that balance was under frequency load shedding (UFLS).

The following UFLS operated on the afternoon of August 14:

- Ohio shed over 1,883 MW beginning at 16:10:39
- Michigan shed a total of 2,835 MW
- New York shed a total of 10,648 MW in several steps, beginning at 16:10:48
- PJM shed a total of 1,324 MW in three steps in northern New Jersey, beginning at 16:10:48
- New England shed a total of 1,098 MW

The entire northeastern system was experiencing large scale, dynamic oscillations during this period. Even if the UFLS and generation had been perfectly balanced at any moment in time, these oscillations would have made stabilization difficult and unlikely.

After the blackout of 1965, the utilities serving New York City and neighboring northern New Jersey increased the integration between the systems serving this area to increase the flow capability into New York and improve the reliability of the system as a whole. The combination of the facilities in place and the pattern of electrical loads and flows on August 14 caused New York to be tightly linked electrically to northern New Jersey and southwestern Connecticut, and moved previously existing weak spots on the grid out past this combined load and network area.

New York-New England Separation: 16:10:46 to 16:10:54 EDT

Prior to New England's separation from the Eastern Interconnection at approximately 16:11, voltages became depressed due to the large power swings occurring across the interconnection while trying to feed the collapsing areas to the west. Immediately following the separation of New England and the Maritimes from the Eastern Interconnection, the Connecticut transmission system voltages went high.

This was the result of capacitors remaining in service, load loss, reduced reactive losses on transmission circuits, and loss of generation to regulate the system voltage. Overvoltage protective relays operated, tripping both transmission and distribution capacitors across the Connecticut system. In addition, the load in the area of Connecticut that was still energized began to increase during the first 7–10 minutes following the initial separation as loads reconnected. This increase in load was most likely due to customers restoring process load, which tripped during transient instability. The load increase combined with the capacitors tripping resulted in the transmission voltages going from high to low within approximately five minutes. To stabilize the system, New England operators ordered all fast start generation by 16:16 and took decisive action to manually drop approximately 80 MW of load in southwest Connecticut by 16:39. They dropped another 325 MW in Connecticut and 100 MW in western Massachusetts by 16:40. These measures helped to stabilize the New England and Maritime island following their separation from the rest of the Eastern Interconnection.

Between 16:10:46 and 16:10:54, the separation between New England and New York occurred along five northern ties and seven ties within southwestern Connecticut. At the time of the east-west separation in New York at 16:10:49, New England was isolated from the eastern New York island. The only remaining tie was the PV-20 circuit connecting New England and the western New York island, which tripped at 16:10:54. Because New England was exporting to New York before the disturbance across the southwestern Connecticut tie, but importing on the Norwalk-Northport tie, the Pleasant Valley path opened east of Long Mountain (in other words, internal to southwestern Connecticut) rather than along the actual New York-New England tie. Immediately before the separation, the power swing out of New England occurred because the New England generators had increased output in response to the drag of power through Ontario and New York into Michigan and Ohio. The power swings continuing through the region caused this separation and caused Vermont to lose approximately 70 MW of load.

When the ties between New York and New England disconnected, most of New England, along with the Maritime provinces of New Brunswick and Nova Scotia, became an island with generation and demand balanced sufficiently close that it was able to remain operational. The New England system had been exporting close to 600 MW to New York, so it was relatively generation-rich and experienced continuing fluctuations until it reached equilibrium. Before the Maritimes and New England separated from the Eastern Interconnection at approximately 16:11, voltages became depressed across portions of New England and some large customers disconnected themselves automatically. However, southwestern Connecticut separated from New England and remained tied to the New York system for about one minute.

While frequency within New England fluctuated slightly and recovered quickly after 16:10:40, frequency in the New York-Ontario-Michigan-Ohio island varied severely as additional lines, loads, and generators tripped, reflecting the magnitude of the generation deficiency in Michigan and Ohio.

Due to its geography and electrical characteristics, the Québec system in Canada is tied to the remainder of the Eastern Interconnection via high-voltage DC links instead of AC transmission lines. Québec was able to survive the power surges with only small impacts because the DC connections shielded it from the frequency swings. At the same time, the DC ties into upper New York and New England served as resources to stabilize those two islands and helped keep them energized during the cascade.

New York Transmission Split East-West: 16:10:49 EDT

The transmission system split internally within New York along the Total East interface, with the eastern portion islanding to contain New York City, northern New Jersey, and southwestern Connecticut. The eastern New York island had been importing energy, so it did not have enough surviving generation online to balance load. Frequency declined quickly to below 58.0 Hz and triggered 7,115 MW of automatic UFLS. Frequency declined further, as did voltage, causing pre-designed trips at the Indian Point nuclear plant and other generators in and around New York City through 16:11:10. New York's Total East and Central East interfaces, where the New York internal split occurred, are routinely among the most heavily loaded paths in the state and are operated under thermal, voltage, and stability limits to respect their relative vulnerability and importance.

Examination of the loads and generation in the eastern New York island indicates that before 16:10:00, the area had been importing electricity and had less generation on-line than load. At 16:10:50, seconds after the separation along the Total East interface, the eastern New York area had experienced significant load reductions due to UFLS — Consolidated Edison, which serves New York City and surrounding areas, dropped more than 40 percent of its load on automatic UFLS. But at this time, the system was still experiencing dynamic conditions; frequency was falling, flows and voltages were oscillating, and power plants were tripping off-line. Had there been a slow islanding situation and more generation on-line, it might have been possible for the Eastern New York island to rebalance given its high level of UFLS. However, events happened so quickly and the power swings were so large that rebalancing would have been unlikely, with or without the northern New Jersey and southwestern Connecticut loads hanging onto eastern New York. This was further complicated because the high rate of change in voltages at load buses reduced the actual levels of load shed by UFLS relative to the levels needed and expected.

Western New York-Ontario Interface

The Ontario system separated from the western New York island just west of Niagara Falls and west of St. Lawrence at 16:10:50. This separation was due to relay operations that disconnected nine 230-kV lines within Ontario. These left most of Ontario isolated. Ontario's large Beck and Saunders hydro stations, along with some Ontario load, the NYPA Niagara and St. Lawrence hydro stations, and NYPA's 765-kV AC interconnection to their HVDC tie with Québec, remained connected to the western New York system, supporting the demand in upstate New York. From 16:10:49 to 16:10:50, frequency in Ontario declined below 59.3 Hz, initiating automatic UFLS (3,000 MW). This load shedding dropped about 12 percent of Ontario's remaining load. Between 16:10:50 and 16:10:56, the isolation of Ontario's 2,300 MW Beck and Saunders hydro units onto the western New York island, coupled with UFLS, caused the frequency in this island to rise to 63.4 Hz due to excess generation relative to the load remaining within the island. The high frequency caused trips of five of the U.S. nuclear units within the island, and the last one tripped on the second frequency rise.

Three of the 230-kV transmission circuits reclosed near Niagara automatically to reconnect Ontario to New York at 16:10:56. Even with these lines reconnected, the main Ontario island (still attached to New York and eastern Michigan) was extremely deficient in generation, so its frequency declined towards 58.8 Hz, the threshold for the second stage of UFLS. Over the next two seconds, another 19 percent of Ontario demand (4,800 MW) automatically disconnected by UFLS. At 16:11:10, these same three lines tripped a second time west of Niagara, and New York and most of Ontario separated for a final time. Following this separation, the frequency in Ontario declined to 56 Hz by 16:11:57. With Ontario still supplying 2,500 MW to the Michigan-Ohio load pocket, the remaining ties with Michigan tripped at 16:11:57.
Ontario system frequency declined, leading to a widespread shutdown at 16:11:58 and a loss of 22,500 MW of load in Ontario, including the cities of Toronto, Hamilton, and Ottawa.

Southwest Connecticut Separated From New York City: 16:11:22 EDT

In southwestern Connecticut, when the Long Mountain-Plum Tree line disconnected at 16:11:22, it left about 500 MW of demand supplied only through a 138-kV underwater tie to Long Island. About two seconds later, the two 345-kV circuits connecting southeastern New York to Long Island tripped, isolating Long Island and southwestern Connecticut, which remained tied together by the underwater Norwalk Harbor to Northport 138-kV cable. The cable tripped about 20 seconds later, causing southwestern Connecticut to black out.

Western New York Stabilizes

Within the western New York island, the 345-kV system remained intact from Niagara east to the Utica area, and from the St. Lawrence/Plattsburgh area south to the Utica area through both the 765-kV and 230-kV circuits. Ontario's Beck and Saunders generation remained connected to New York at Niagara and St. Lawrence, respectively, and this island stabilized with about 50 percent of the pre-event load remaining. The boundary of this island moved southeastward as a result of the reclosure of Fraser-to-Coopers Corners 345-kV at 16:11:23.

Eastern New York Island Splits

As a result of the severe frequency and voltage changes, many large generating units in New York and Ontario tripped off-line. The eastern island of New York, including the heavily populated areas of southeastern New York, New York City, and Long Island, experienced severe frequency and voltage decline. At 16:11:29, the New Scotland-to-Leeds 345-kV circuits tripped, separating the eastern New York island into northern and southern sections. The small remaining load in the northern portion of the eastern island (the Albany area) retained electric service, supplied by local generation until it could be resynchronized with the western New York island. The southern island, including New York City, rapidly collapsed into a blackout.

Remaining Transmission Lines Between Ontario and Eastern Michigan Separate: 16:11:57 EDT

Before the blackout, New England, New York, Ontario, eastern Michigan, and northern Ohio were scheduled net importers of power. When the western and southern lines serving Cleveland, Toledo, and Detroit collapsed, most of the load remained on those systems, but some generation had tripped. This exacerbated the generation/load imbalance in areas that were already importing power. The power to serve this load came through the only major path available, via Ontario. After most of IMO was separated from New York and generation to the north and east, much of the Ontario load and generation was lost; it took only moments for the transmission paths west from Ontario to Michigan to fail.

When the cascade was over at about 16:12, much of the disturbed area was completely blacked out, but isolated pockets still had service because load and generation had reached equilibrium. Ontario's large Beck and Saunders hydro stations, along with some Ontario load, the NYPA

Niagara and St. Lawrence hydro stations, and NYPA's 765-kV AC interconnection to the Québec HVDC tie, remained connected to the western New York system, supporting demand in upstate New York.

Cascading Sequence Essentially Complete: 16:13 EDT

Most of the Northeast (the area shown in gray in Figure 12) had now blacked out. Some isolated areas of generation and load remained on-line for several minutes. Some of those areas in which a close generation-demand balance could be maintained remained operational.

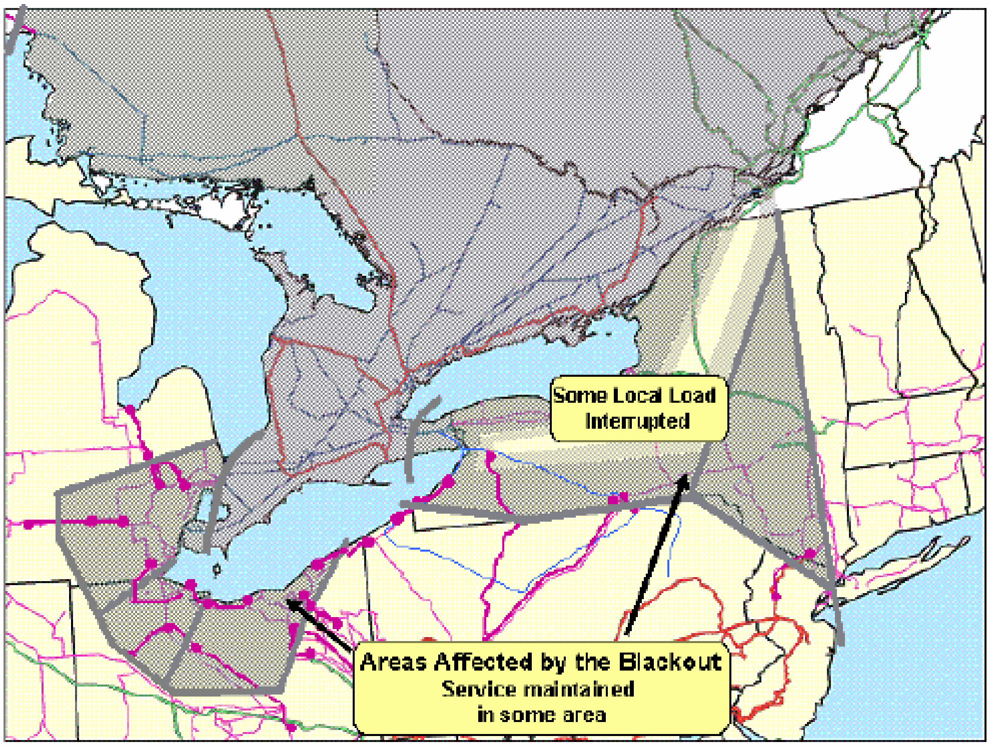

Figure 12 - Areas Affected by the Blackout

One relatively large island remained in operation, serving about 5,700 MW of demand, mostly in western New York. Ontario's large Beck and Saunders hydro stations, along with some Ontario load, the NYPA Niagara and St. Lawrence hydro stations, and NYPA's 765-kV AC interconnection with Québec, remained connected to the western New York system, supporting demand in upstate New York. This island formed the basis for restoration in both New York and Ontario.

V. Summary

The August 14 blackout had many similarities with previous large-scale blackouts, including the 1965 Northeast blackout that was the basis for forming NERC in 1968, and the July 1996 outages in the West.

Common factors include: conductor contacts with trees, inability of system operators to visualize events on the system, failure to operate within known safe limits, ineffective operational communications and coordination, inadequate training of operators to recognize and respond to system emergencies, and inadequate reactive power resources.

Investigators found that the Sammis-Star 345-kV line trip was a seminal event, after which power system failures began to spread beyond northeastern Ohio to affect other areas. After the Sammis-Star line outage at 16:05:57, the accelerating cascade of line and generator outages would have been difficult or impossible to stop with installed protection and controls. Therefore, the causes of the blackout are focused on problems that occurred before the Sammis-Star outage.

The causes of the blackout described here did not result from inanimate events, such as “the alarm processor failed” or “a tree contacted a power line.” Rather, the causes of the blackout were rooted in deficiencies resulting from decisions, actions, and the failure to act of the individuals, groups, and organizations involved. These causes were preventable prior to August 14 and are correctable. Simply put — blaming a tree for contacting a line serves no useful purpose. The responsibility lies with the organizations and persons charged with establishing and implementing an effective vegetation management program to maintain safe clearances between vegetation and energized conductors.

Each cause identified here was verified to have existed on August 14 prior to the blackout. Each cause was also determined to be both a necessary condition to the blackout occurring and, in conjunction with the other causes, sufficient to cause the blackout. In other words, each cause was a direct link in the causal chain leading to the blackout and the absence of any one of these causes could have broken that chain and prevented the blackout. This definition distinguishes causes as a subset of a broader category of identified deficiencies. Other deficiencies are noted in the next section; they may have been contributing factors leading to the blackout or may present serious reliability concerns completely unrelated to the blackout, but they were not deemed by the investigators to be direct causes of the blackout. They are still important; however, because they might have caused a blackout under a different set of circumstances.

Causes of the Blackout

The root cause of the outage boils down to three main causes. They are:

1. **FE lacked situational awareness of line outages and degraded conditions on the FE system.**

    a. FE had no alarm failure detection system.
    b. FE computer support staff did not effectively communicate the loss of alarm functionality to the FE system operators after the alarm processor failed at 14:14, nor did they have a formal procedure to do so.
    c. FE control center computer support staff did not fully test the functionality of applications, including the alarm processor, after a server failover and restore.
    d. FE did not have an effective contingency analysis capability cycling periodically on-line and did not have a practice of running contingency analysis manually as an effective alternative for identifying contingency limit violations.

2. **FE did not effectively manage vegetation in its transmission rights-of-way.**

3. **Reliability coordinators did not provide effective diagnostic support.**

    a. MISO was using non-real-time information to monitor real-time operations in its area of responsibility.
    b. MISO did not have real-time topology information for critical lines mapped into its state estimator.
    c. The PJM and MISO reliability coordinators lacked an effective procedure on when and how to coordinate an operating limit violation observed by one of them in the other's area due to a contingency near their common boundary.

Other Deficiencies

The deficiencies listed above were determined by investigators to be necessary and sufficient to cause the August 14 blackout — therefore they are labeled causes. Investigators identified many other deficiencies, which did not meet the "necessary and sufficient" test, and therefore were not labeled as causes of the blackout. In other words, a sufficient set of deficiencies already existed to cause the blackout without these other deficiencies.

However, these other deficiencies represent significant conclusions of the investigation, as many of them aggravated the enabling conditions or the severity of the consequences of the blackout. An example is the ninth deficiency listed below, regarding poor communications within the FE control center. Poor communications within the control center did not cause the blackout and the absence of those poor communications within the FE control center would not have prevented the blackout. However, poor communications in the control center was a contributing factor, because it increased the state of confusion in the control center and exacerbated the FE operators' lack of situational awareness. The investigators also discovered a few of these deficiencies to be unrelated to the blackout but still of significant concern to system reliability. An example is deficiency number eight: FE was operating close to a voltage collapse in the Cleveland-Akron area, although voltage collapse did not initiate the sequence of events that led to the blackout.

+++