5. The Cascade Stage of the Blackout

Chapter 4 described how uncorrected problems in northern Ohio developed to a point that a cascading blackout became inevitable. However, the Task Force's investigation also sought to understand how and why the cascade spread and stopped as it did. As detailed below, the investigation determined the sequence of events in the cascade, and in broad terms how it spread and how it stopped in each general geographic area.[1]

Why Does a Blackout Cascade?

Major blackouts are rare, and no two blackout scenarios are the same. The initiating events will vary, including human actions or inactions, system topology, and load/generation balances. Other factors that will vary include the distance between generating stations and major load centers, voltage profiles, and the types and settings of protective relays in use.

Most wide-area blackouts start with short circuits (faults) on several transmission lines in short succession—sometimes resulting from natural causes such as lightning or wind or, as on August 14, resulting from inadequate tree management in right-of-way areas. A fault causes a high current and low voltage on the line containing the fault. A protective relay for that line detects the high current and low voltage and quickly trips the circuit breakers to isolate that line from the rest of the power system.

A cascade occurs when there is a sequential tripping of numerous transmission lines and generators in a widening geographic area. A cascade can be triggered by just a few initiating events, as was seen on August 14. Power swings and voltage fluctuations caused by these initial events can cause other lines to detect high currents and low voltages that appear to be faults, even when faults do not actually exist on those other lines. Generators are tripped off during a cascade to protect them from severe power and voltage swings. Relay protection systems work well to protect lines and generators from damage and to isolate them from the system under normal, steady conditions. However, when power system operating and design criteria are violated as a result of several outages occurring at the same time, most common protective relays cannot distinguish between the currents and voltages seen in a system cascade from those caused by a fault. This leads to more and more lines and generators being tripped, widening the blackout area.

How Did the Cascade Evolve on August 14?

At 16:05:57 Eastern Daylight Time, the trip and lock-out of FE's Sammis-Star 345 kV line set off a cascade of interruptions on the high voltage system, causing electrical fluctuations and facility trips as within seven minutes the blackout rippled from the Akron area across much of the northeast United States and Canada. By 16:13 EDT, more than 263 power plants (531 individual generating units) had been lost, and tens of millions of people in the United States and Canada were without electric power.

Chapter 4 described the four phases that led to the initiation of the cascade at about 16:06 EDT. After 16:06 EDT, the cascade evolved in three distinct phases:

- **Phase 5.** The collapse of FE's transmission system induced unplanned power surges across the region. Shortly before the collapse, large electricity flows were moving across FE's system from generators in the south (Tennessee, Kentucky, Missouri) to load centers in northern Ohio, eastern Michigan, and Ontario. This pathway in northeastern Ohio became unavailable with the collapse of FE's transmission system. The electricity then took alternative paths to the load centers located along the shore of Lake Erie. Power surged in from western Ohio and Indiana on one side and from Pennsylvania through New York and Ontario around the northern side of Lake Erie. Transmission lines in these areas, however, were already heavily loaded with normal flows, and some of them began to trip.

- **Phase 6.** The northeast then separated from the rest of the Eastern Interconnection due to these additional power surges. The power surges resulting from the FE system failures caused lines in neighboring areas to see overloads that caused impedance relays to operate. The result was a wave of line trips through western Ohio that separated AEP from FE. Then the line trips progressed northward into Michigan separating western and eastern Michigan.

  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. The relays on the lines between PJM and New York saw this massive power surge as faults and tripped those lines. Lines in western Ontario also became overloaded and tripped. The entire northeastern United States and the province of Ontario then became a large electrical island separated from the rest of the Eastern Interconnection. This large island, which had been importing power prior to the cascade, quickly became unstable as there was not sufficient generation in operation within it 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.

Phase 7. In the final phase, the large electrical island in the northeast was deficient in generation and 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 these smaller islands was often 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 without total loss of service. For example, most of New England was stabilized and generation and load restored to balance. Approximately half of the generation and load remained on in western New York, which has an abundance of generation. By comparison, other areas with large load centers and insufficient generation nearby to meet that load collapsed into a blackout condition (Figure 5.1).

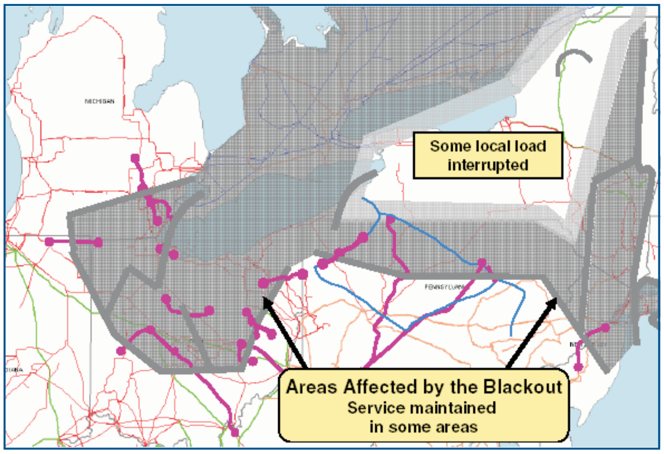
Impedance Relays

The most common protective device for transmission lines is the impedance relay (also known as a distance relay). It detects changes in currents and voltages to determine the apparent impedance of the line. A relay is installed at each end of a transmission line. Each relay is actually three relays within one, with each element looking at a particular "zone" or length of the line being protected.

- The first zone looks for faults on the line itself, with no intentional delay.
- The second zone is set to look at the entire line and slightly beyond the end of the line with a slight time delay. The slight delay on the zone 2 relay is useful when a fault occurs near one end of the line. The zone 1 relay near that end operates quickly to trip the circuit breakers on that end. However, the zone 1 relay on the far end may not be able to tell if the fault is just inside the line or just beyond the line. In this case, the zone 2 relay on the far end trips the breakers after a short delay, allowing the zone 1 relay near the fault to open the line on that end first.
- The third zone is slower acting and looks for faults well beyond the length of the line. It can be thought of as a backup, but would generally not be used under normal conditions.

An impedance relay operates when the apparent impedance, as measured by the current and voltage seen by the relay, falls within any one of the operating zones for the appropriate amount of time for that zone. The relay will trip and cause circuit breakers to operate and isolate the line. Typically, Zone 1 and 2 operations are used to protect lines from faults. Zone 3 relay operations, as in the August 14 cascade, can occur if there are apparent faults caused by large swings in voltages and currents.

Figure 5.1. Area Affected by the Blackout



What Stopped the August 14 Blackout from Cascading Further?

The investigation concluded that one or more of the following likely determined where and when the cascade stopped spreading:

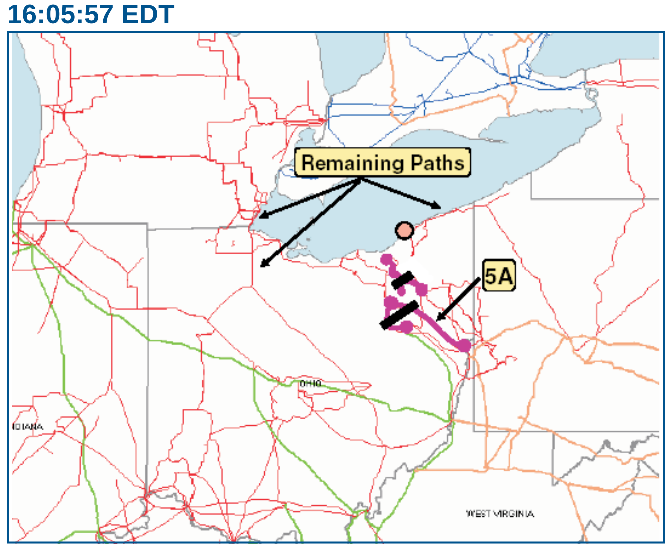
- The effects of a disturbance travel over power lines and become dampened the further they are from the initial point, much like the ripple from a stone thrown in a pond. Thus, the voltage and current swings seen by relays on lines farther away from the initial disturbance are not as severe, and at some point they are no longer sufficient to induce lines to trip.
- Higher voltage lines and more densely networked lines, such as the 500-kV system in PJM and the 765-kV system in AEP, are better able to absorb voltage and current swings and thus serve as a barrier to the spreading of a cascade. As seen in Phase 6, the cascade progressed into western Ohio and then northward through Michigan through the areas that had the fewest transmission lines. Because there were fewer lines, each line absorbed more of the power and voltage surges and was more vulnerable to tripping. A similar effect was seen toward the east as the lines between New York and Pennsylvania, and eventually northern New Jersey tripped. The cascade of transmission line outages became isolated after the northeast United States and Ontario were completely separated from the rest of the Eastern Interconnection and no more power flows were possible into the northeast (except the DC ties from Quebec, which continued to supply power to western New York and New England).
- Some areas, due to line trips, were isolated from the portion of the grid that was experiencing instability. Many of these areas retained sufficient on-line generation or the capacity to import power from other parts of the grid, unaffected by the surges or instability, to meet demand. As the cascade progressed, and more generators and lines tripped off to protect themselves from severe damage, and some areas completely separated from the unstable part of the Eastern Interconnection. In many of these areas there was sufficient generation to stabilize the system. After the large island was formed in the northeast, symptoms of frequency and voltage collapse became evident. In some parts of the large area, the system was too unstable and shut itself down. In other parts, there was sufficient generation, coupled with fast-acting automatic load shedding, to stabilize frequency and voltage. In this manned, most of New England remained energized. Approximately half of the generation and load remained on in western New York, aided by generation in southern Ontario that split and stayed with western New York. There were other smaller isolated pockets of load and generation that were able to achieve equilibrium and remain energized.

Phase 5: 345-kV Transmission System Cascade in Northern Ohio and South-Central Michigan

Overview of This Phase

This initial phase of the cascade began because after the loss of FE's Sammis-Star 345-kV line and the underlying 138-kV system, there were no large transmission paths left from the south to support the significant amount of load in northern Ohio (Figure 5.2). This placed a significant load burden

Figure 5.2. Sammis-Star 345-kV Line Trip, 16:05:57 EDT



onto the transmission paths north and northwest into Michigan, causing a steady loss of lines and power plants.

Key Events in This Phase

5A) 16:05:57 EDT: Sammis-Star 345-kV tripped.

5B) 16:08:59 EDT: Galion-Ohio Central-Muskingum 345-kV line tripped.

5C) 16:09:06 EDT: East Lima-Fostoria Central 345-kV line tripped, causing major power swings through New York and Ontario into Michigan.

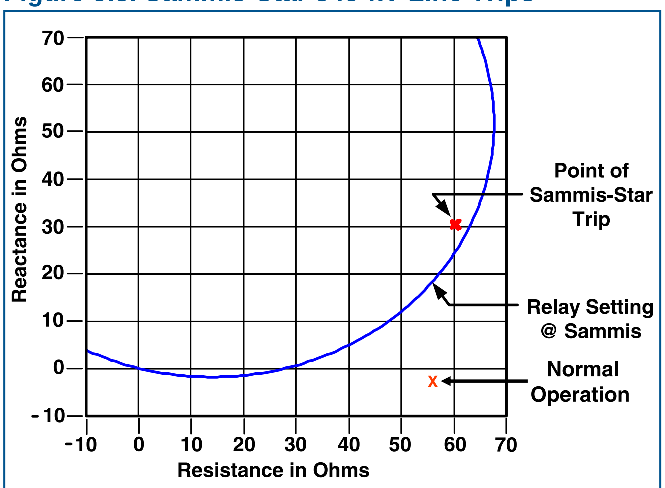
5D) 16:09:08 EDT to 16:10:27 EDT: Several power plants lost, totaling 937 MW.

5A) Sammis-Star 345-kV Tripped: 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 relay action that measured low apparent impedance (depressed voltage divided by abnormally high line current) (Figure 5.3). There was no fault and no major power swing at the time of the trip—rather, high flows above 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 an exceptionally high line-load condition. Moreover, the reactive flows (VArs) on the line were almost ten times higher than they had been earlier in the day. The relay operated as it was designed to do.

The Sammis-Star 345-kV line trip completely severed the 345-kV path into northern Ohio from southeast 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 northern Ohio: (1) from northwest Pennsylvania to northern Ohio around the south shore of Lake Erie, (2) from southern 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 5.3. Sammis-Star 345-kV Line Trips



Transmission Lines into Northwestern Ohio Tripped, and Generation Tripped in South Central Michigan and Northern Ohio: 16:08:59 EDT to 16:10:27 EDT

5B) Galion-Ohio Central-Muskingum 345-kV line tripped: 16:08:59 EDT

5C) East Lima-Fostoria Central 345-kV line tripped, causing a large power swing from Pennsylvania and New York through Ontario to Michigan: 16:09:05 EDT

The tripping of the Galion-Ohio Central-Muskingum and East Lima-Fostoria Central 345-kV 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

> ***System Oscillations***
>
> The electric power system constantly experiences small, stable power oscillations. They occur as generator rotors accelerate or slow down while rebalancing electrical output power to mechanical input power, to respond to changes in load or network conditions. These oscillations are observable in the power flow on transmission lines that link generation to load or in the tie lines that link different regions of the system together. The greater the disturbance to the network, the more severe these oscillations can become, even to the point where flows become so great that protective relays trip the connecting lines, just as a rubber band breaks when stretched too far. If the lines connecting different electrical regions separate, each region will drift to its own frequency.
>
> Oscillations that grow in amplitude are called unstable oscillations. Oscillations are also sometimes called power swings, and once initiated they flow back and forth across the system rather like water sloshing in a rocking tub.

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 northeast Ohio to northwest Pennsylvania along the southern shore of Lake Erie, and (2) westward by lines west and northwest of Detroit, Michigan and from Michigan into Ontario (Figure 5.4).

The East Lima-Fostoria Central 345-kV line tripped at 16:09:06 EDT due to high currents and low voltage, and the resulting large power swings (measuring about 400 MW when they passed through NYPA's Niagara recorders) marked the moment when the system became unstable. This was the first of several inter-area power and frequency events that occurred over the next two minutes. It was the system's response to the loss of the Ohio-Michigan transmission paths (above), and the stress that the still-high Cleveland, Toledo and Detroit loads put onto the surviving lines and local generators.

In Figure 5.5, a high-speed recording of 345-kV flows past Niagara Falls shows the New York to Ontario power swing, which continued to oscillate for over 10 seconds. The recording shows the magnitude of subsequent flows triggered by the trips of the Hampton-Pontiac and Thetford-Jewell 345-kV lines in Michigan and the Perry-Ashtabula 345-kV line linking the Cleveland area to Pennsylvania. The very low voltages on the northern Ohio transmission system made it very difficult for the generation in the Cleveland and Lake Erie area to maintain synchronization with the Eastern Interconnection. 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.

Before this first major power swing on the Michigan/Ontario interface, power flows in the NPCC Region (Ontario and the Maritimes, New England, New York, and the mid-Atlantic portion of PJM) were typical for the summer period, and well within acceptable limits. Transmission and generation facilities were then in a secure state across the NPCC.

5D) Multiple Power Plants Tripped, Totaling 937 MW: 16:09:08 to 16:10:27 EDT

Michigan Cogeneration Venture plant reduction of 300 MW (from 1,263 MW to 963 MW)

Kinder Morgan units 1 and 2 trip (200 MW total)

Avon Lake 7 unit trips (82 MW)

Berger 3, 4, and 5 units trip (355 MW total)

The Midland Cogeneration Venture (MCV) plant is in central Michigan. Kinder Morgan is in south-central Michigan. The large power reversal caused frequency and voltage fluctuations at the plants. Their automatic control systems responded to these transients by trying to adjust output to raise voltage or respond to the frequency changes, but subsequently tripped off-line. The Avon Lake and Burger units, in or near Cleveland, likely tripped off due to the low voltages prevailing in the Cleveland area and 138-kV line trips near Burger 138-kV substation (northern Ohio) (Figure 5.6).

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

Figure 5.4. Ohio 345-kV Lines Trip, 16:08:59 to 16:09:07 EDT

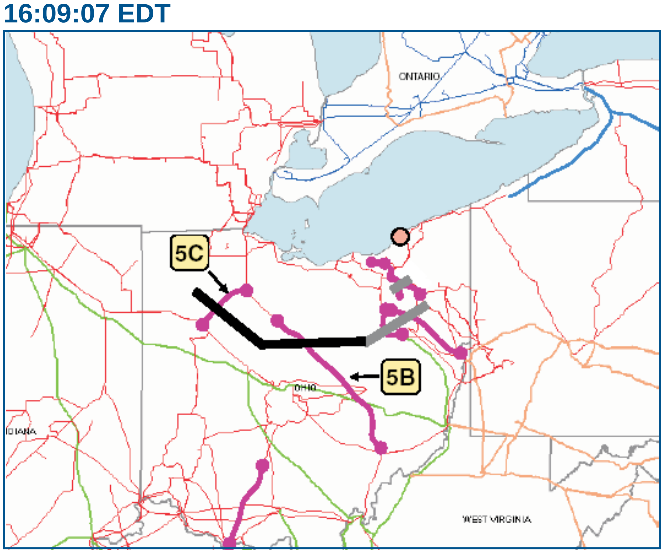
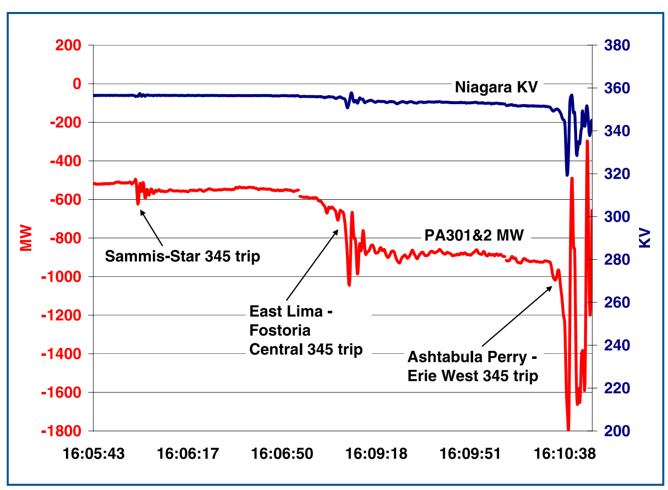


Figure 5.5. New York-Ontario Line Flows at Niagara



Note: Does not include 230-kV line flow.

dropped from the imbalance between high loads and limited transmission and generation capability.

Phase 6: The Full Cascade

Between 16:10:36 EDT and 16:13 EDT, thousands of events occurred on the grid, driven by physics and automatic equipment operations. When it was over, much of the northeast United States and the Canadian province of Ontario was in the dark.

Key Phase 6 Events

Transmission Lines Disconnected Across Michigan and Northern Ohio, Generation Shut Down in Central Michigan and Northern Ohio, and Northern Ohio Separated from Pennsylvania: 16:10:36 EDT to 16:10:39 EDT

6A) Transmission and more generation tripped within Michigan: 16:10:36 EDT to 16:10:37 EDT:

Argenta-Battlecreek 345-kV line tripped

Battlecreek-Oneida 345-kV line tripped

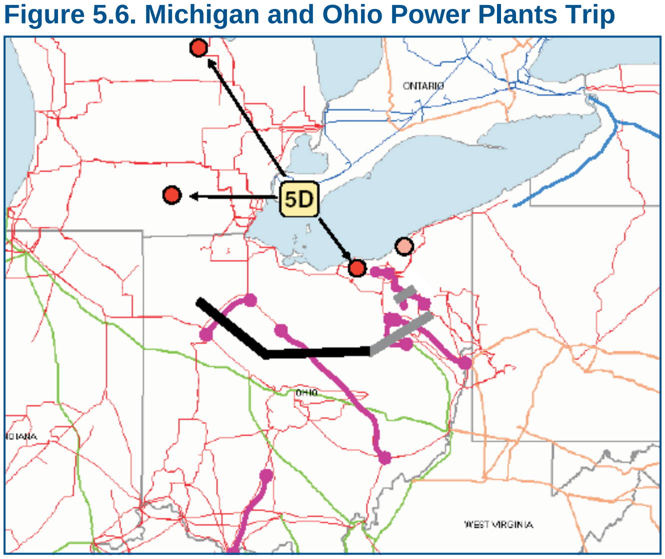
Argenta-Tompkins 345-kV line tripped

Sumpter Units 1, 2, 3, and 4 units tripped (300 MW near Detroit)

MCV Plant output dropped from 944 MW to 109 MW.

Together, the above line outages interrupted the east-to-west transmission paths into the Detroit area from south-central Michigan. The Sumpter generation units tripped in response to under-voltage on the system. Michigan lines northwest of Detroit then began to trip, as noted below (Figure 5.7).

Figure 5.6. Michigan and Ohio Power Plants Trip



6B) More Michigan lines tripped: 16:10:37 EDT to 16:10:38 EDT

Hampton-Pontiac 345-kV line tripped

Thetford-Jewell 345-kV line tripped

These 345-kV lines connect Detroit to the north. When they tripped out of service, it left the loads in Detroit, Toledo, Cleveland, and their surrounding areas served only by local generation and the lines connecting Detroit east to Ontario and Cleveland east to northeast Pennsylvania.

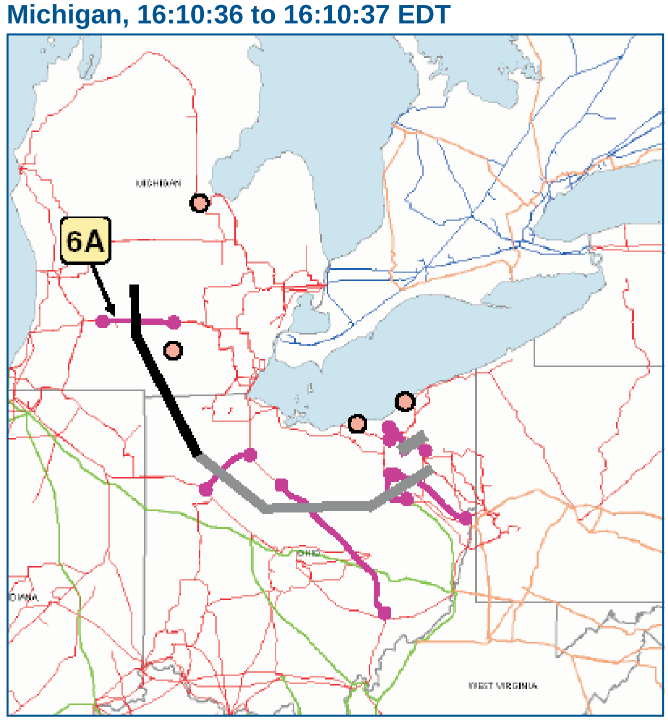
6C) Cleveland separated from Pennsylvania, flows reversed and a huge power surge flowed counter-clockwise around Lake Erie: 16:10:38.6 EDT

Perry-Ashtabula-Erie West 345-kV line tripped: 16:10:38.6 EDT

Large power surge to serve loads in eastern Michigan and northern Ohio swept across Pennsylvania, New Jersey, and New York through Ontario into Michigan: 16:10:38.6 EDT.

Perry-Ashtabula-West Erie was the last 345-kV line connecting northern Ohio to the east. This line's trip separated the Ohio 345-kV transmission system from Pennsylvania. When it tripped, the load centers in eastern Michigan and northern Ohio remained connected to the rest of the Eastern Interconnection only at the interface between the

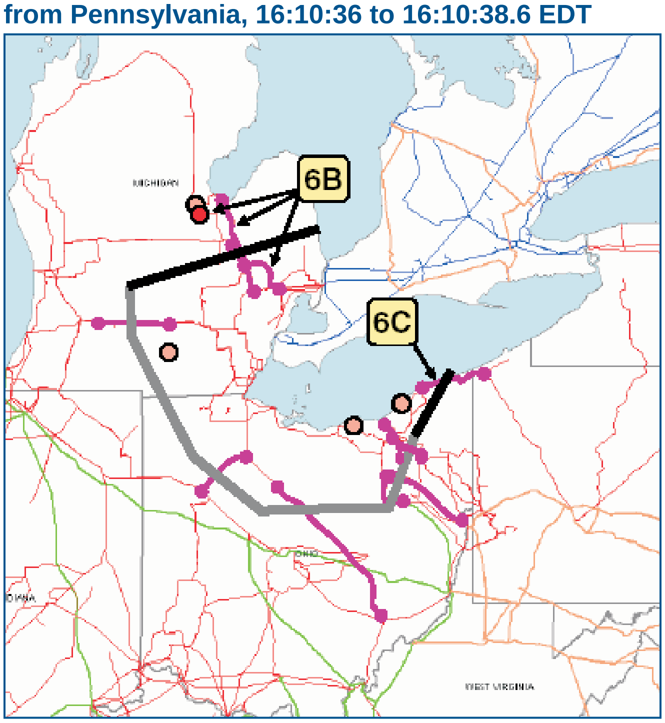
Figure 5.7. Transmission and Generation Trips in Michigan, 16:10:36 to 16:10:37 EDT



Michigan and Ontario systems (Figure 5.8). Eastern Michigan and northern Ohio now had little internal generation left and voltage was declining. Between 16:10:39 EDT and 16:10:50 EDT under-frequency load shedding in the Cleveland area operated and interrupted about 1,750 MW of load. The frequency in the Cleveland area (by then separated from the Eastern Interconnection to the south) was also dropping rapidly and the load shedding was not enough to arrest the frequency decline. Since the electrical system always seeks to balance load and generation, the high loads in Cleveland drew power over the only major transmission path remaining—the lines from eastern Michigan east into Ontario.

Before the loss of the Perry-Ashtabula-West Erie line, 437 MW was flowing from Michigan into Ontario. At 16:10:38.6 EDT, after the other transmission paths into Michigan and Ohio failed, the power that had been flowing over them reversed direction in a fraction of a second. Electricity began flowing toward Michigan via a giant loop through Pennsylvania and into New York and Ontario and then into Michigan via the remaining transmission path. Flows at Niagara Falls 345-kV lines measured over 800 MW, and over 3,500 MW at the Ontario to Michigan interface (Figure 5.9). This sudden large change in power flows drastically lowered voltage and increased current levels on the transmission lines along the Pennsylvania-New York transmission interface.

Figure 5.8. Michigan Lines Trip and Ohio Separates from Pennsylvania, 16:10:36 to 16:10:38.6 EDT

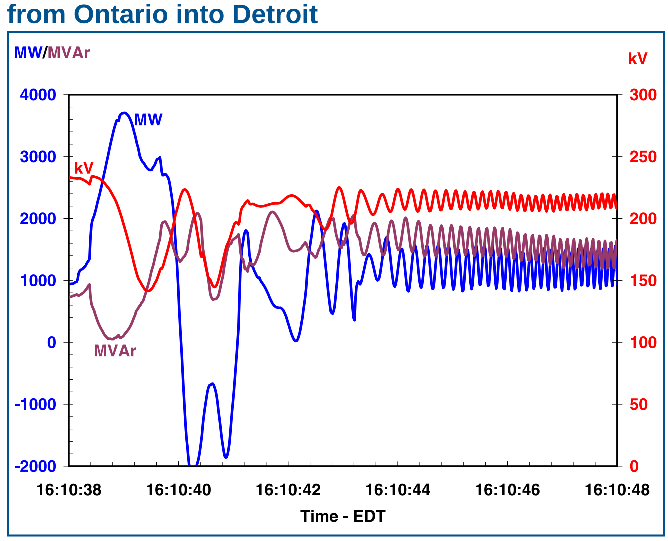


This was a transient frequency swing, so frequency was not the same across the Eastern Interconnection. As Figure 5.8 shows, this frequency imbalance and the accompanying power swing resulted in a rapid rate of voltage decay. Flows into Detroit exceeded 3,500 MW and 1,500 MVAr, meaning that the power surge was draining both active and reactive power out of the northeast to prop up the low voltages in eastern Michigan and Detroit. This magnitude of reactive power draw caused voltages in Ontario and New York to drop. At the same time, local voltages in the Detroit area were low because there was still not enough supply to meet load. Detroit would soon black out (as evidenced by the rapid power swings decaying after 16:10:43 EDT).

Between 16:10:38 and 16:10:41 EDT, the power surge caused a sudden extraordinary increase in system frequency to 60.3 Hz. A series of circuits tripped along the border between PJM and the NYISO due to apparent impedance faults (short circuits). The surge also moved into New England and the Maritimes region of Canada. The combination of the power surge and frequency rise caused 380 MW of pre-selected Maritimes generation to drop 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 failure 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.

In summary, the Perry-Ashtabula-Erie West 345-kV line trip at 16:10:38.6 EDT was the point when the Northeast entered a period of transient instability and a loss of generator synchronism.

Figure 5.9. Active and Reactive Power and Voltage from Ontario into Detroit



Western Pennsylvania Separated from New York: 16:10:39 EDT to 16:10:44 EDT

6D) 16:10:39 EDT, Homer City-Watercure Road 345-kV

Homer City-Stolle Road 345-kV: 16:10:39 EDT

6E) South Ripley-Erie East 230-kV, and South Ripley-Dunkirk 230-kV: 16:10:44 EDT

East Towanda-Hillside 230-kV: 16:10:44 EDT

Responding to the surge of power flowing north out of Pennsylvania through New York and Ontario into Michigan, relays on these lines activated on apparent impedance within a five-second period and separated Pennsylvania from New York (Figure 5.10).

At this point, the northern part of the Eastern Interconnection (including eastern Michigan and northern Ohio) remained 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 northeast New Jersey, and (2) in the west through the long and therefore fragile 230-kV transmission path connecting Ontario to Manitoba and Minnesota.

Figure 5.10. Western Pennsylvania Separates from New York, 16:10:39 EDT to 16:10:44 EDT

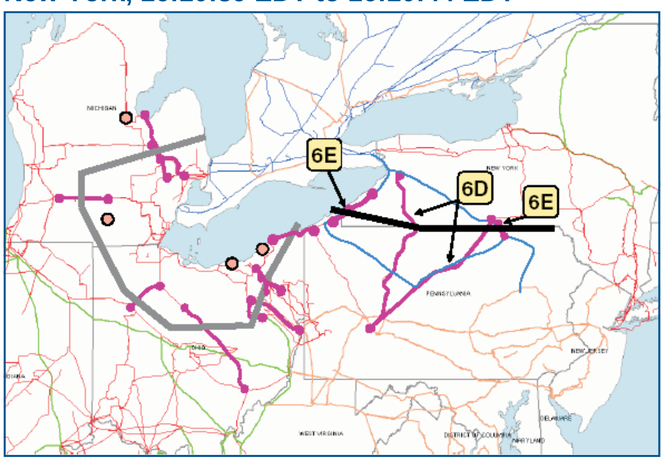
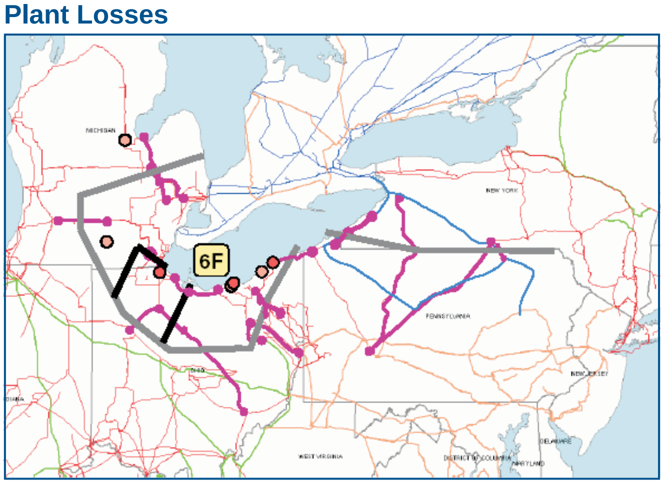


Figure 5.11. More Transmission Line and Power Plant Losses



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.

6F) Conditions in Northern Ohio and Eastern Michigan Degraded Further, With More Transmission Lines and Power Plants Failing: 16:10:39 to 16:10:46 EDT

Bayshore-Monroe 345-kV line

Allen Junction-Majestic-Monroe 345-kV line

Majestic 345-kV Substation: one terminal opened on all 345-kV lines

Perry-Ashtabula-Erie West 345-kV line terminal at Ashtabula 345/138-kV substation

Fostoria Central-Galion 345-kV line

Beaver-Davis Besse 345-kV line

Galion-Ohio Central-Muskingum 345 tripped at Galion

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

Lakeshore unit 18 (156 MW, near Cleveland)

Bay Shore Units 1-4 (551 MW near Toledo)

Eastlake 1, 2, and 3 units (403 MW total, near Cleveland)

Avon Lake unit 9 (580 MW, near Cleveland)

Perry 1 nuclear unit (1,223 MW, near Cleveland)

Ashtabula unit 5 (184 MW, near Cleveland)

Back in northern Ohio, the trips of the Majestic 345-kV substation in southeast Michigan, the Bay Shore-Monroe 345-kV line, and the Ashtabula 345/138-kV transformer created a Toledo and Cleveland electrical "island" (Figure 5.11). Frequency in this large island began to fall rapidly. This led to a series of power plants in the area shutting down due to the operation of underfrequency relays, including the Bay Shore units. When the Beaver-Davis Besse 345-kV line connecting Cleveland and Toledo tripped, it left the Cleveland area completely isolated. Cleveland area load was disconnected by automatic underfrequency load-shedding (approximately 1,300

MW in the greater Cleveland area), and another 434 MW of load was interrupted after the generation remaining within this transmission "island" was tripped by under-frequency relays. 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 prolonged period of system-wide low voltage around Detroit caused the remaining generators in that area, then running at maximum mechanical output, to begin to pull out of synchronous operation with the rest of the grid. Those plants raced ahead of system frequency with higher than normal revolutions per second by each generator. But when voltage returned to near-normal, the generator could not fully pull back its rate of revolutions, and ended up producing excessive temporary output levels, still out of step with the system. This is evident in Figure 5.9 (above), which shows at least two sets of generator "pole slips" by plants in the Detroit area between 16:10:40 EDT and 16:10:42 EDT. Several large units around Detroit—Belle River, St. Clair, Greenwood, Monroe and Fermi—all recorded tripping for out-of-step operation due to this cause. The Perry 1 nuclear unit, located on the southern shore of Lake Erie near the border with Pennsylvania, and a number of other units near Cleveland tripped off-line by unit under-frequency protection.

6G) Transmission paths disconnected in New Jersey and northern Ontario, isolating the northeast portion of the Eastern Interconnection: 16:10:42 EDT to 16:10:45 EDT

- Four power plants producing 1,630 MW tripped off-line
  - Greenwood unit 11 and 12 tripped (225 MW near Detroit)
  - Belle River unit 1 tripped (600 MW near Detroit)
  - St. Clair unit 7 tripped (221 MW, DTE unit)
  - Trenton Channel units 7A, 8 and 9 tripped (584 MW, DTE units)
- Keith-Waterman 230-kV tripped, 16:10:43 EDT
- Wawa-Marathon W21-22 230-kV line tripped, 16:10:45 EDT
- Branchburg-Ramapo 500-kV line tripped, 16:10:45 EDT

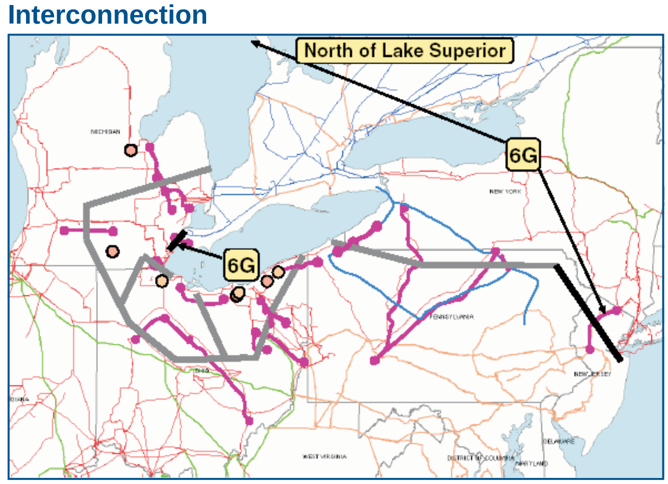
A significant amount of the remaining generation serving Detroit tripped off-line in response to these events. At 16:10:43 EDT, eastern Michigan was still connected to Ontario, but the Keith-Waterman 230-kV line that forms part of that interface disconnected due to apparent impedance (Figure 5.12).

At 16:10:45 EDT, northwest Ontario separated from the rest of Ontario when the Wawa-Marathon 230-kV lines disconnected along the northern shore of Lake Superior. 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.

The Branchburg-Ramapo 500-kV line 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 EDT along with the underlying 230 and 138-kV lines in northeast New Jersey. 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.

At this point, the Eastern Interconnection was split 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 Maritime 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.

Figure 5.12. Northeast Disconnects from Eastern Interconnection



Phase 7: Several Electrical Islands Formed in Northeast U.S. and Canada: 16:10:46 EDT to 16:12 EDT

Overview of This Phase

New England (except southwestern Connecticut) and the Maritimes separated from New York and remained intact; New York split east to west: 16:10:46 EDT to 16:11:57 EDT. Figure 5.13 illustrates the events of this phase.

During the next 3 seconds, the islanded northern section of the Eastern Interconnection broke apart internally.

7A) New York-New England transmission lines disconnected: 16:10:46 EDT to 16:10:47 EDT

7B) 16:10:49 EDT, New York transmission system split east to west

7C) The Ontario system just west of Niagara Falls and west of St. Lawrence separated from the western New York island: 16:10:50 EDT

7D) Southwest Connecticut separated from New York City: 16:11:22 EDT

7E) Remaining transmission lines between Ontario and eastern Michigan separated: 16:11:57 EDT

Key Phase 7 Events

7A) New York-New England Transmission Lines Disconnected: 16:10:46 EDT to 16:10:49 EDT

Over the period 16:10:46 EDT to 16:10:49 EDT, the New York to New England tie lines tripped. The power swings continuing through the region caused this separation, and caused Vermont to lose approximately 70 MW of load.

The ties between New York and New England disconnected, and most of the New England area along with Canada's Maritime Provinces became an island with generation and demand balanced close enough that it was able to remain operational. New England had been exporting close to 600 MW to New York, and its system experienced continuing fluctuations until it reached electrical equilibrium. Before the Maritimes-New England separated from the Eastern Interconnection at approximately 16:11 EDT, voltages became depressed due to the large power swings across portions of New England. Some large customers disconnected themselves automatically.[2] However, southwestern Connecticut separated from New England and remained tied to the New York system for about 1 minute.

Due to its geography and electrical characteristics, the Quebec system in Canada is tied to the remainder of the Eastern Interconnection via high voltage DC links instead of AC transmission lines. Quebec was able to survive the power surges with only small impacts because the DC connections shielded it from the frequency swings.

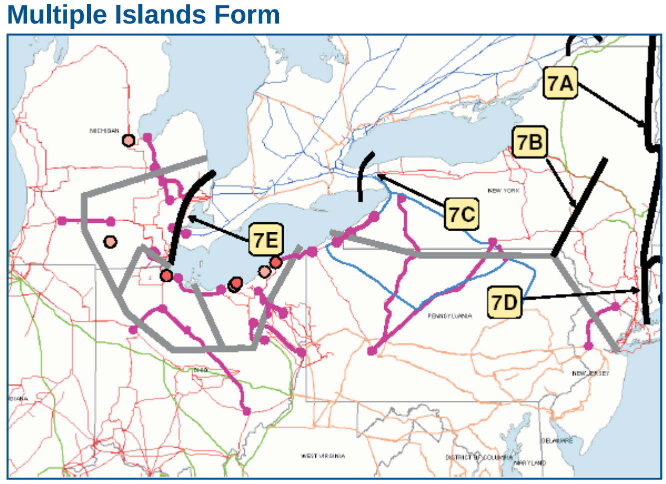
7B) New York Transmission Split East-West: 16:10:49 EDT

The transmission system split internally within New York, with the eastern portion islanding to contain New York City, northern New Jersey and southwestern Connecticut. The western portion of New York remained connected to Ontario and eastern Michigan.

7C) The Ontario System Just West of Niagara Falls and West of St. Lawrence Separated from the Western New York Island: 16:10:50 EDT

At 16:10:50 EDT, Ontario and New York separated west of the Ontario/New York interconnection, due to relay operations which disconnected nine 230-kV lines within Ontario. These left most of Ontario isolated to the north. Ontario's large Beck and Saunders hydro stations, along with some Ontario load, the New York Power Authority's (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 the demand in upstate New York.

Figure 5.13. New York and New England Separate, Multiple Islands Form



From 16:10:49 EDT to 16:10:50 EDT, frequency declined below 59.3 Hz, initiating automatic under-frequency load-shedding in Ontario (2,500 MW), eastern New York and southwestern Connecticut. This load-shedding dropped off about 20% of the load across the eastern New York island and about 10% of Ontario's remaining load. Between 16:10:50 EDT and 16:10:56 EDT, the isolation of the southern Ontario hydro units onto the western New York island, coupled with under-frequency load-shedding in the western New York island, caused the frequency in this island to rise to 63.0 Hz due to excess generation.

Three of the tripped 230-kV transmission circuits near Niagara automatically reconnected Ontario to New York at 16:10:56 EDT by reclosing. Even with these lines reconnected, the main Ontario island (still attached to New York and eastern Michigan) was then extremely deficient in generation, so its frequency declined towards 58.8 Hz, the threshold for the second stage of under-frequency load-shedding. Within the next two seconds another 18% of Ontario demand (4,500 MW) automatically disconnected by under-frequency load-shedding. At 16:11:10 EDT, 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 EDT. With Ontario still supplying 2,500 MW to the Michigan-Ohio load pocket, the remaining ties with Michigan tripped at 16:11:57 EDT. Ontario system frequency declined, leading to a widespread shutdown at 16:11:58 EDT and loss of 22,500 MW of load in Ontario, including the cities of Toronto, Hamilton and Ottawa.

7D) Southwest Connecticut Separated from New York City: 16:11:22 EDT

In southwest Connecticut, when the Long Mountain-Plum Tree line (connected to the Pleasant Valley substation in New York) disconnected at 16:11:22 EDT, it left about 500 MW of southwest Connecticut 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 southwest Connecticut, which remained tied together by the underwater Norwalk Harbor to Northport 138-kV cable. The cable tripped about 20 seconds later, causing southwest Connecticut to black out.

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% 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 EDT.

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

Under-frequency Load-Shedding

Since in an electrical system load and generation must balance, if a system loses a great deal of generation suddenly it will if necessary drop load to balance that loss. Unless that load drop is managed carefully, such an imbalance can lead to a voltage collapse and widespread outages. In an electrical island with declining frequency, if sufficient load is quickly shed, frequency will begin to rise back toward 60 Hz.

After the blackouts of the 1960s, some utilities installed under-frequency load-shedding mechanisms on their distribution systems. These systems are designed to drop pre-designated customer load automatically if frequency gets too low (since low frequency indicates too little generation relative to load), starting generally when frequency reaches 59.2 Hz. Progressively more load is set to drop as frequency levels fall farther. The last step of customer load shedding is set at the frequency level just above the set point for generation under-frequency protection relays (57.5 Hz), to prevent frequency from falling so low that the generators could be damaged (see Figure 2.4).

Not every utility or control area handles load-shedding in the same way. In NPCC, following the Northeast blackout of 1965, the region adopted automatic load-shedding criteria to prevent a recurrence of the cascade and better protect system equipment from damage due to a high-speed system collapse.

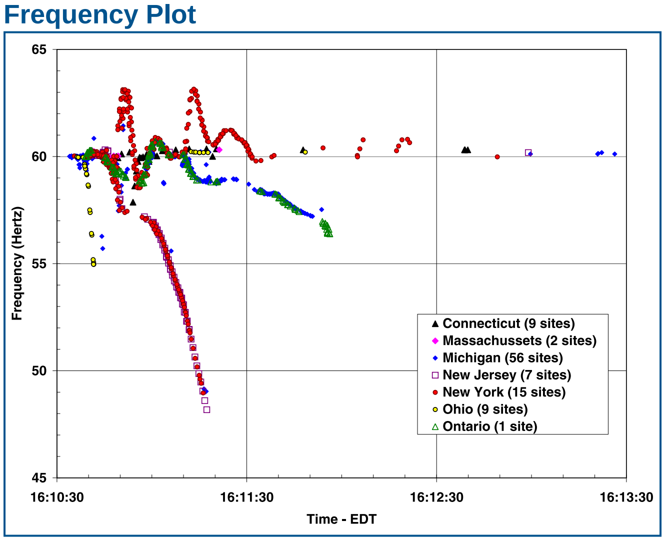
New York, including the heavily populated areas of southeastern New York, New York City, and Long Island, experienced severe frequency and voltage decline. At 16:11:29 EDT, the New Scotland to Leeds 345-kV circuits tripped, separating the island into northern and southern sections. The small remaining 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.

7E) Remaining Transmission Lines Between Ontario and Eastern Michigan Separated: 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, through Ontario (IMO). 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 EDT, much of the disturbed area was completely blacked out, but there were isolated pockets that still had service because load and generation had reached equilibrium. Ontario's large Beck and Saunders hydro stations, along with some Ontario load, the New York Power Authority's (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.

Figure 5.14. Electric Islands Reflected in Frequency Plot



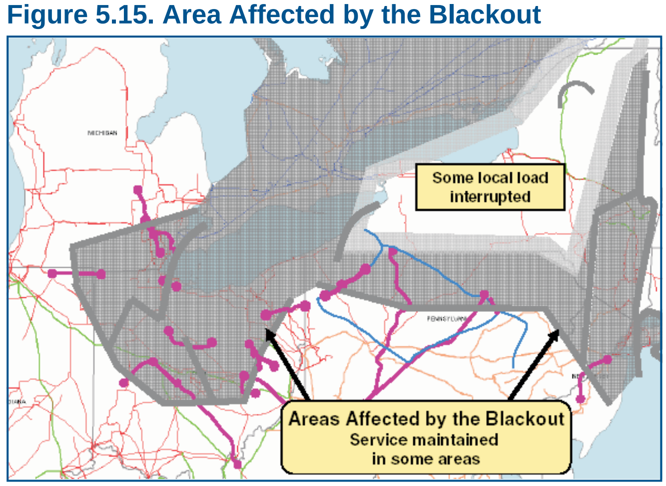
Electrical islanding. Once the northeast became isolated, it grew generation-deficient as more and more power plants tripped off-line to protect themselves from the growing disturbance. The severe swings in frequency and voltage in the area caused numerous lines to trip, so the isolated area broke further into smaller islands. The load/generation mismatch also affected voltages and frequency within these smaller areas, causing further generator trips and automatic under-frequency load-shedding, leading to blackout in most of these areas.

Figure 5.14 shows frequency data collected by the distribution-level monitors of Softswitching Technologies, Inc. (a commercial power quality company serving industrial customers) for the area affected by the blackout. The data reveal at least five separate electrical islands in the Northeast as the cascade progressed. The two paths of red diamonds on the frequency scale reflect the Albany area island (upper path) versus the New York city island, which declined and blacked out much earlier.

Cascading Sequence Essentially Complete: 16:13 EDT

Most of the Northeast (the area shown in gray in Figure 5.15) was 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; other generators ultimately tripped off line and the areas they served were blacked out.

Figure 5.15. Area 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 New York Power Authority's (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.

The entire cascade sequence is depicted graphically in Figure 5.16 on the following page.

Why the Blackout Stopped Where It Did

Extreme system conditions can damage equipment in several ways, from melting aluminum conductors (excessive currents) to breaking turbine blades on a generator (frequency excursions). The power system is designed to ensure that if conditions on the grid (excessive or inadequate voltage, apparent impedance or frequency) threaten the safe operation of the transmission lines, transformers, or power plants, the threatened equipment automatically separates from the network to protect itself from physical damage. Relays are the devices that effect this protection.

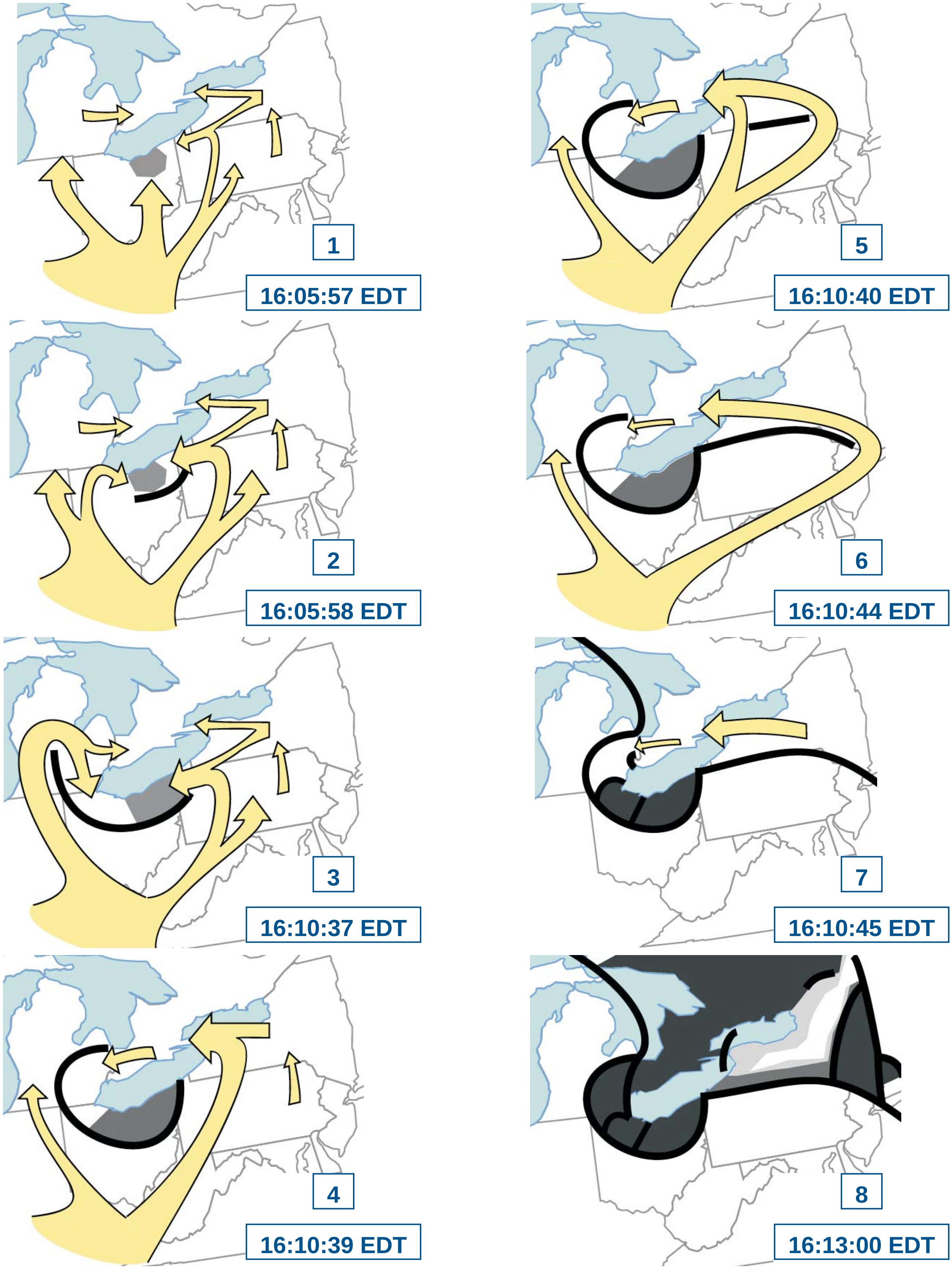
Generators are usually the most expensive units on an electrical system, so system protection schemes are designed to drop a power plant off the system as a self-protective measure if grid conditions become unacceptable. When unstable power swings develop between a group of generators that are losing synchronization (matching frequency) with the rest of the system, the only way to stop the oscillations is to stop the flows entirely by separating all interconnections or ties between the unstable generators and the remainder of the system. The most common way to protect generators from power oscillations is for the transmission system to detect the power swings and trip at the locations detecting the swings—ideally before the swing reaches and harms the generator.

On August 14, the cascade became a race between the power surges and the relays. The lines that tripped first were generally the longer lines, because the relay settings required to protect these lines use a longer apparent impedance tripping zone, which a power swing enters sooner, in comparison to the shorter apparent impedance zone targets set on shorter, networked lines. On August 14, relays on long lines such as the Homer City-Watercure and the Homer City-Stolle Road 345-kV lines in Pennsylvania, that are not highly integrated into the electrical network, tripped quickly and split the grid between the sections that blacked out and those that recovered without further propagating the cascade. This same phenomenon was seen in the Pacific Northwest blackouts of 1996, when long lines tripped before more networked, electrically supported lines.

Transmission line voltage divided by its current flow is called "apparent impedance." Standard transmission line protective relays continuously measure apparent impedance. When apparent impedance drops within the line's protective relay set-points for a given period of time, the relays trip the line. The vast majority of trip operations on lines along the blackout boundaries between PJM and New York (for instance) show high-speed relay targets, which indicate that massive power surges caused each line to trip. To the relays, this massive power surge altered the voltages and currents enough that they appeared to be faults. This power surge was caused by power flowing to those areas that were generation-deficient. These flows occurred purely because of the physics of power flows, with no regard to whether the power flow had been scheduled, because power flows from areas with excess generation into areas that are generation-deficient.

Relative voltage levels across the northeast affected which areas blacked out and which areas stayed on-line. Within the Midwest, there were relatively low reserves of reactive power, so as voltage levels declined many generators in the affected area were operating at maximum reactive power output before the blackout. This left the system little slack to deal with the low voltage conditions by ramping up more generators to higher reactive power output levels, so there was little room to absorb any system "bumps" in voltage or frequency. In contrast, in the northeast—particularly PJM, New York, and ISO-New England—operators were anticipating high power demands on the afternoon of August 14, and had already set up the system to maintain higher voltage levels and therefore had more reactive reserves on-line in anticipation of later afternoon needs. Thus, when the voltage and frequency swings began, these systems had reactive power already or readily available to help buffer their areas against a voltage collapse without widespread generation trips.

Figure 5.16. Cascade Sequence



Legend: Yellow arrows represent the overall pattern of electricity flows. Black lines represent approximate points of separation between areas within the Eastern Interconnect. Gray shading represents areas affected by the blackout.

Voltage Collapse

Although the blackout of August 14 has been labeled as a voltage collapse, it was not a voltage collapse as that term has been traditionally used by power system engineers. Voltage collapse typically occurs on power systems that are heavily loaded, faulted (reducing the number of available paths for power to flow to loads), or have reactive power shortages. The collapse is initiated when reactive power demands of loads can no longer be met by the production and transmission of reactive power. A classic voltage collapse occurs when an electricity system experiences a disturbance that causes a progressive and uncontrollable decline in voltage. Dropping voltage causes a further reduction in reactive power from capacitors and line charging, and still further voltage reductions. If the collapse continues, these voltage reductions cause additional elements to trip, leading to further reduction in voltage and loss of load. At some point the voltage may stabilize but at a much reduced level. In summary, the system begins to fail due to inadequate reactive power supplies rather than due to overloaded facilities.

On August 14, the northern Ohio electricity system did not experience a classic voltage collapse because low voltage never became the primary cause of line and generator tripping. Although voltage was a factor in some of the events that led to the ultimate cascading of the system in Ohio and beyond, the event was not a classic reactive power-driven voltage collapse. Rather, although reactive power requirements were high, voltage levels were within acceptable bounds before individual transmission trips began, and a shortage of reactive power did not trigger the collapse. Voltage levels began to degrade, but not collapse, as early transmission lines were lost due to tree-line contacts causing ground faults. With fewer lines operational, current flowing over the remaining lines increased and voltage decreased (current increases in inverse proportion to the decrease in voltage for a given amount of power flow). Soon, in northern Ohio, lines began to trip out automatically on protection from overloads, rather than from insufficient reactive power. As the cascade spread beyond Ohio, it spread due not to insufficient reactive power, but because of dynamic power swings and the resulting system instability.

On August 14, voltage collapse in some areas was a result, rather than a cause, of the cascade. Significant voltage decay began after the system was already in an N-3 or N-4 contingency situation. Frequency plots over the course of the cascade show areas with too much generation and others with too much load as the system attempted to reach equilibrium between generation and load. As the transmission line failures caused load to drop off, some parts of the system had too much generation, and some units tripped off on over-frequency protection. Frequency fell, more load dropped on under-frequency protection, the remaining generators sped up and then some of them tripped off, and so on. For a period, conditions see-sawed across the northeast, ending with isolated pockets in which generation and load had achieved balance, and wide areas that had blacked out before an equilibrium had been reached.

Why the Generators Tripped Off

At least 263 power plants with more than 531 individual generating units shut down in the August 14 blackout. These U.S. and Canadian plants can be categorized as follows:

By reliability coordination area:

- Hydro Quebec, 5 plants
- Ontario, 92 plants
- ISO-New England, 31 plants
- MISO, 30 plants
- New York ISO, 67 plants
- PJM, 38 plants

By type:

- Conventional steam units, 67 plants (39 coal)
- Combustion turbines, 66 plants (36 combined cycle)
- Nuclear, 10 plants—7 U.S. and 3 Canadian, totaling 19 units (the nuclear unit outages are discussed in Chapter 7)
- Hydro, 101
- Other, 19

There were three categories of generator shutdowns:

1. Excitation system failures during extremely low voltage conditions on portions of the power system
2. Plant control system actions after major disturbances to in-plant thermal/mechanical systems
3. Consequential tripping due to total system disconnection or collapse.

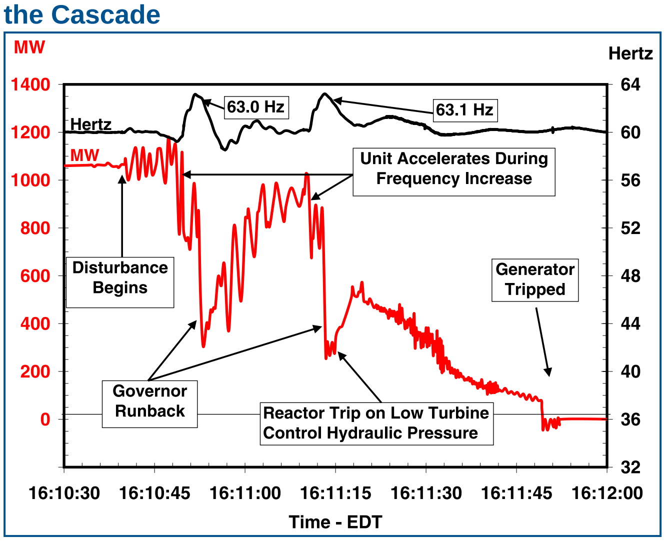
Examples of the three types of separation are discussed below.

Excitation failures. The Eastlake 5 trip at 1:31 p.m. was an excitation system failure—as voltage fell at the generator bus, the generator tried to increase its production of voltage on the coil (excitation) quickly. This caused the generator's excitation protection scheme to trip the plant off to protect its windings and coils from over-heating. Several of the other generators which tripped early in the cascade came off under similar circumstances as excitation systems were over-stressed to hold voltages up.

After the cascade was initiated, huge power swings across the torn transmission system and excursions of system frequency put all the units in their path through a sequence of major disturbances that shocked several units into tripping. Plant controls had actuated fast governor action on several of these to turn back the throttle, then turn it forward, only to turn it back again as some frequencies changed several times by as much as 3 Hz (about 100 times normal). Figure 5.17 is a plot of the MW output and frequency for one large unit that nearly survived the disruption but tripped when in-plant hydraulic control pressure limits were eventually violated. After the plant control system called for shutdown, the turbine control valves closed and the generator electrical output ramped down to a preset value before the field excitation tripped and the generator breakers opened to disconnect the unit from the system.

Plant control systems. The second reason for power plant trips was actions or failures of plant control systems. One common cause in this category was a loss of sufficient voltage to in-plant loads. Some plants run their internal cooling and processes (house electrical load) off the generator or off small, in-house auxiliary generators, while others take their power off the main grid. When large power swings or voltage drops reached these plants in the latter category, they tripped off-line because the grid could not supply the plant's in-house power needs reliably.

Figure 5.17. Events at One Large Generator During the Cascade



Consequential trips. Most of the unit separations fell in the third category of consequential tripping—they tripped off-line in response to some outside condition on the grid, not because of any problem internal to the plant. Some generators became completely removed from all loads; because the fundamental operating principle of the grid is that load and generation must balance, if there was no load to be served the power plant shut down in response to over-speed and/or over-voltage protection schemes. Others were overwhelmed because they were among a few power plants within an electrical island, and were suddenly called on to serve huge customer loads, so the imbalance caused them to trip on under-frequency and/or under-voltage protection. A few were tripped by special protection schemes that activated on excessive frequency or loss of pre-studied major transmission elements known to require large blocks of generation rejection.

The maps in Figure 5.18 show the sequence of power plants lost in three blocks of time during the cascade.

The investigation team is still analyzing data on the effect of the cascade on the affected generators, to learn more about how to protect generation and transmission assets and speed system restoration in the future.

Endnotes

[1] The extensive computer modeling required to determine the expansion and cessation of the blackout (line by line, relay by relay, generator by generator, etc.) has not been performed.

[2] After New England's separation from the Eastern Interconnection occurred, the next several minutes were critical to stabilizing the ISO-NE system. Voltages in New England recovered and over-shot to high due to the combination of load loss, capacitors still in service, lower reactive losses on the transmission system, and loss of generation to regulate system voltage. Over-voltage protective relays operated to trip both transmission and distribution capacitors. Operators in New England brought all fast-start generation on-line by 16:16 EDT. Much of the customer process load was automatically restored. This caused voltages to drop again, putting portions of New England at risk of voltage collapse. Operators manually dropped 80 MW of load in southwest Connecticut by 16:39 EDT, another 325 MW in Connecticut and 100 MW in western Massachusetts by 16:40 EDT. These measures helped to stabilize their island following their separation from the rest of the Eastern Interconnection.

Figure 5.18. Power Plants Tripped During the Cascade