6. The Cascade Stage of the Blackout

Chapter 5 described how uncorrected problems in northern Ohio developed to 16:05:57 EDT, the last point at which a cascade of line trips could have been averted. 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 how and why it spread, and how it stopped in each general geographic area.

Based on the investigation to date, the investigation team concludes that the cascade spread beyond Ohio and caused such a widespread blackout for three principal reasons. First, the loss of the Sammis-Star 345-kV line in Ohio, following the loss of other transmission lines and weak voltages within Ohio, triggered many subsequent line trips. Second, many of the key lines which tripped between 16:05:57 and 16:10:38 EDT operated on zone 3 impedance relays (or zone 2 relays set to operate like zone 3s) which responded to overloads rather than true faults on the grid. The speed at which they tripped spread the reach and accelerated the spread of the cascade beyond the Cleveland-Akron area. Third, the evidence collected indicates that the relay protection settings for the transmission lines, generators and under-frequency load-shedding in the northeast may not be entirely appropriate and are certainly not coordinated and integrated to reduce the likelihood and consequences of a cascade—nor were they intended to do so. These issues are discussed in depth below.

This analysis is based on close examination of the events in the cascade, supplemented by complex, detailed mathematical modeling of the electrical phenomena that occurred. At the completion of this report, the modeling had progressed through 16:10:40 EDT, and was continuing. Thus this chapter is informed and validated by modeling (explained below) up until that time. Explanations after that time reflect the investigation team's best hypotheses given the available data, and may be confirmed or modified when the modeling is complete. However, simulation of these events is so complex that it may be impossible to ever completely prove these or other theories about the fast-moving events of August 14. Final modeling results will be published by NERC as a technical report in several months.

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 across the grid, and the types and settings of protective relays in use.

Some 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 is a dynamic phenomenon that cannot be stopped by human intervention once started. It 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 if 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. Protective relay systems work well to protect lines and generators from damage and to isolate them from the system under normal and abnormal system conditions.

But when power system operating and design criteria are violated because several outages occur simultaneously, commonly used protective relays that measure low voltage and high current 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?

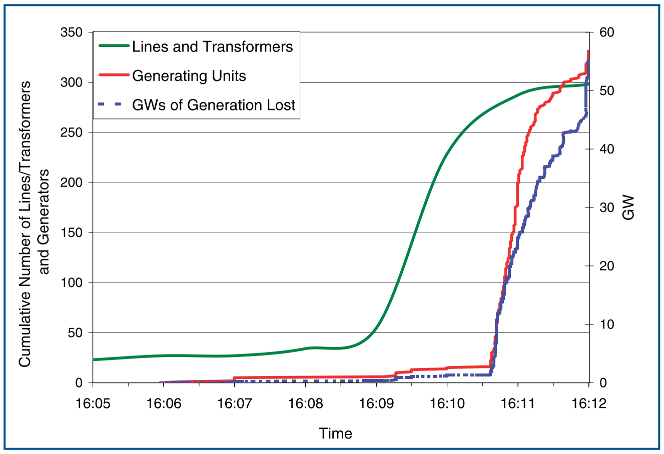
A series of line outages in northeast Ohio starting at 15:05 EDT caused heavy loadings on parallel circuits, leading to the trip and lock-out of FE's Sammis-Star 345-kV line at 16:05:57 Eastern Daylight Time. This was the event that triggered a cascade of interruptions on the high voltage system, causing electrical fluctuations and facility trips such that within seven minutes the blackout rippled from the Cleveland-Akron area across much of the northeast United States and Canada. By 16:13 EDT, 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 events in the cascade started relatively slowly. Figure 6.1 illustrates how the number of lines and generation lost stayed relatively low during the Ohio phase of the blackout, but then picked up speed after 16:08:59 EDT. The cascade was complete only three minutes later.

Chapter 5 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 shifts of power across the region. Shortly before the collapse, large (but normal) electricity flows were moving across FE's system from generators in the south (Tennessee and Kentucky) and west (Illinois and Missouri) to load centers in northern Ohio, eastern Michigan, and Ontario. A series of lines within northern Ohio tripped under the high

Figure 6.1. Rate of Line and Generator Trips During the Cascade



Impedance Relays

The most common protective device for transmission lines is the impedance (Z) relay (also known as a distance relay). It detects changes in currents (I) and voltages (V) to determine the apparent impedance ($Z=V/I$) 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 over 80% of the line next to the relay, with no time delay before the trip.
- 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 other 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, after the zone 1 relay near the fault opens the line on that end first.
- The third zone is slower acting and looks for line faults and faults well beyond the length of the line. It can be thought of as a remote relay or breaker backup, but should not trip the breakers under typical emergency 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. All three relay zone operations protect lines from faults and may trip from apparent faults caused by large swings in voltages and currents.

loads, hastened by the impact of Zone 3 impedance relays. This caused a series of shifts in power flows and loadings, but the grid stabilized after each.

- **Phase 6.** After 16:10:36 EDT, 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, causing a power flow reversal within Michigan toward Cleveland. Many of these line trips were from Zone 3 impedance relay actions that accelerated the speed of the line trips and reduced the potential time in which grid operators might have identified the growing problem and acted constructively to contain it.

  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. Relays on the lines between PJM and New York saw this massive power surge as faults and tripped those lines. Ontario's east-west tie line also became overloaded and tripped, leaving northwest 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. This large area, which had been importing power prior to the cascade, quickly became unstable after 16:10:38 as 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.

- **Phase 7.** In the final phase, after 16:10:46 EDT, 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 these smaller islands was often unbalanced, leading to further tripping of lines and generating units until equilibrium was established in each island.

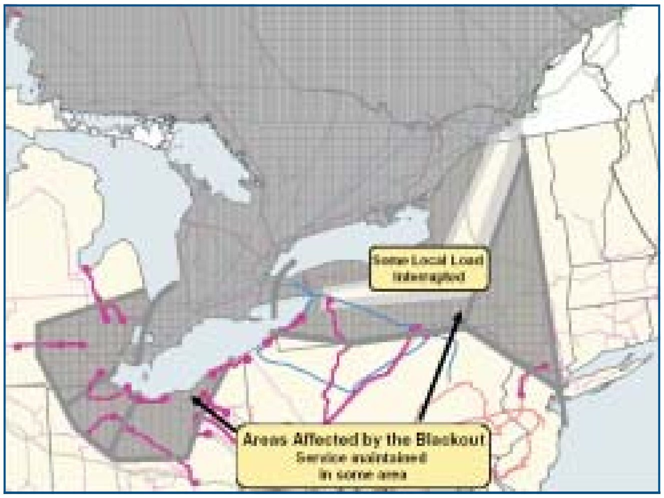
  Although much of the disturbance area was fully blacked out in this process, some islands were able to reach equilibrium without total loss of service. For example, the island consisting of most of New England and the Maritime Provinces stabilized and generation and load returned to balance. Another 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. This island survived but some other areas with large load centers within the island collapsed into a blackout condition (Figure 6.2).

What Stopped the August 14 Blackout from Cascading Further?

The investigation concluded that a combination of the following factors determined where and when the cascade stopped spreading:

- The effects of a disturbance travel over power lines and become damped 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 cause 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 spread 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

Figure 6.2. Area Affected by the Blackout



System Oscillations, Stable, Transient, and Dynamic Conditions

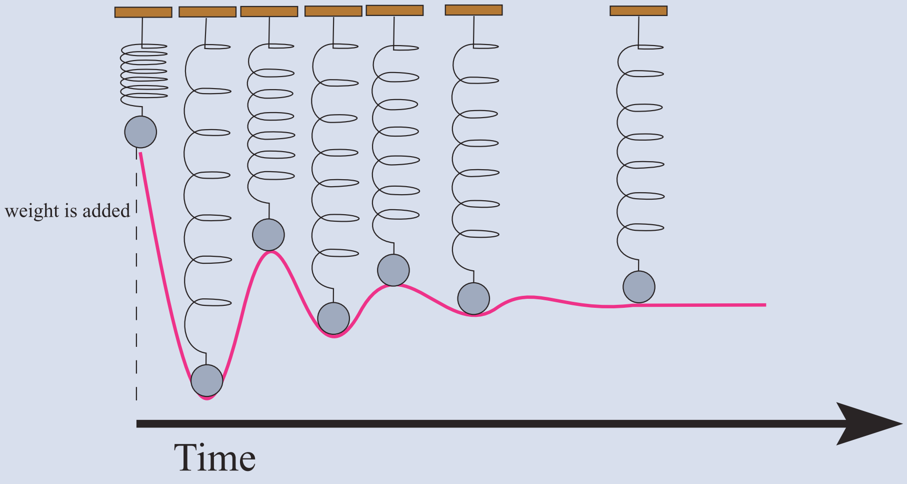
The electric power system constantly experiences small power oscillations that do not lead to system instability. They occur as generator rotors accelerate or slow down while rebalancing electrical output power to mechanical input power, to respond to changes in load or network conditions. These oscillations 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. But with a disturbance to the network, the oscillations can become more severe, even to the point where flows become progressively so great that protective relays trip the connecting lines. If the lines connecting different electrical regions separate, each region will find its own frequency, depending on the load to generation balance at the time of separation.

Oscillations that grow in amplitude are called unstable oscillations. Such oscillations, once initiated, cause power to flow back and forth across the system like water sloshing in a rocking tub.

In a stable electric system, if a disturbance such as a fault occurs, the system will readjust and rebalance within a few seconds after the fault clears. If a fault occurs, protective relays can trip in less than 0.1 second. If the system recovers and rebalances within less than 3 seconds, with the possible loss of only the faulted element and a few generators in the area around the fault, then that condition is termed “transiently stable.” If the system takes from 3 to 30 seconds to recover and stabilize, it is “dynamically stable.” But in rare cases when a disturbance occurs, the system may appear to rebalance quickly, but it then over-shoots and the oscillations can grow, causing widespread instability that spreads in terms of both the magnitude of the oscillations and in geographic scope. This can occur in a system that is heavily loaded, causing the electrical distance (apparent impedance) between generators to be longer, making it more difficult to keep the machine angles and speeds synchronized. In a system that is well damped, the oscillations will settle out quickly and return to a steady balance. If the oscillation continues over time, neither growing nor subsiding, it is a poorly damped system.

The illustration below, of a weight hung on a spring balance, illustrates a system which oscillates over several cycles to return to balance. A critical point to observe is that in the process of hunting for its balance point, the spring overshoots the true weight and balance point of the spring and weight combined, and must cycle through a series of exaggerated overshoots and underweight rebounds before settling down to rest at its true balance point. The same process occurs on an electric system, as can be observed in this chapter.

If a system is in transient instability, the oscillations following a disturbance will grow in magnitude rather than settle out, and it will be unable to readjust to a stable, steady state. This is what happened to the area that blacked out on August 14, 2003.



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 contained 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 Québec, which continued to supply power to western New York and New England).

- Line trips isolated some areas 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, some areas completely separated from the unstable part of the Eastern Interconnection. In many of these areas there was sufficient generation to match load and stabilize the system. After the large island was formed in the northeast, symptoms of frequency and voltage decay emerged. In some parts of the northeast, the system became 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 manner, most of New England and the Maritime Provinces 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

After the loss of FE's Sammis-Star 345-kV line 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 (Figure 6.3). This overloaded the transmission paths west and northwest into Michigan, causing a sequential loss of lines and power plants.

Key Events in This Phase

5A) 16:05:57 EDT: Sammis-Star 345-kV tripped by zone 3 relay.

5B) 16:08:59 EDT: Galion-Ohio Central-Muskingum 345-kV line tripped on zone 3 relay.

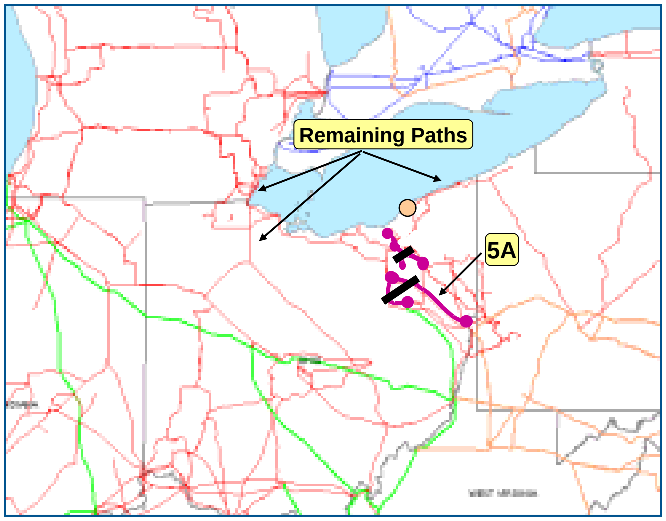
5C) 16:09:06 EDT: East Lima-Fostoria Central 345-kV line tripped on zone 3 relay, causing major power swings through New York and Ontario into Michigan.

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 zone 3 relay action that measured low apparent impedance (depressed voltage divided by abnormally high line current) (Figure 6.4). 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 (VAr) on the line were almost ten times higher than they had been earlier in the day because of the current overload. The relay operated as it was designed to do.

Figure 6.3. Sammis-Star 345-kV Line Trip, 16:05:57 EDT

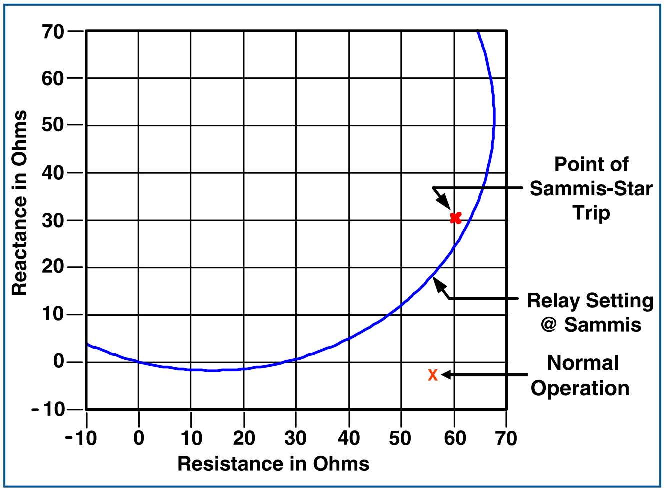


The Sammis-Star 345-kV line trip completely severed the 345-kV path into northern Ohio from southeast Ohio, triggering a new, fast-paced sequence of 345-kV transmission line trips in which each line trip placed a greater flow burden on those lines remaining in service. These line outages left only three paths for power to flow into western Ohio: (1) from northwest Pennsylvania to northern Ohio around the south shore of Lake Erie, (2) from southwest Ohio toward northeast 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. The impact of this trip was felt across the grid—it caused a 100 MW increase in flow from PJM into New York and through to Ontario.[1] Frequency in the Eastern Interconnection increased momentarily by 0.02 Hz.

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 EDT on under-voltage.

During the period between the Sammis-Star trip and the trip of East Lima-Fostoria at 16:09:06.3 EDT, 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. This is illustrated in Figure 6.5, which shows the MW flows on the Michigan Electrical Coordinated Systems (MECS) interfaces with AEP (Ohio), FirstEnergy (Ohio) and Ontario. The graph shows a shift from 150 MW imports to 200 MW exports from the MECS system into FirstEnergy at 16:05:57 EDT 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 bounced somewhat before stabilizing, roughly, until the path across Michigan was cut at 16:10:38 EDT.

Figure 6.4. Sammis-Star 345-kV Line Trip



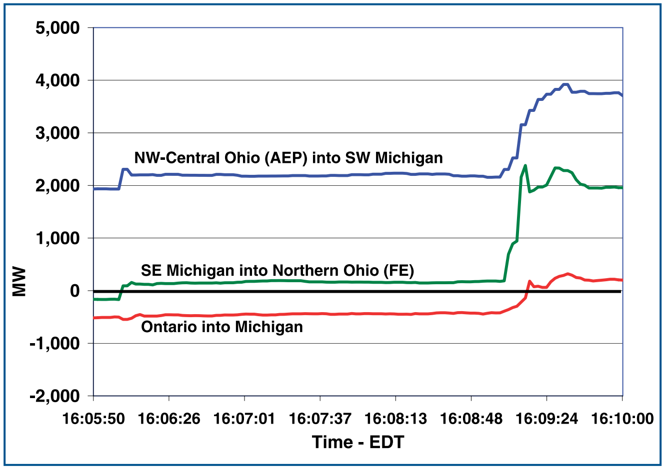
Transmission Lines into Northwestern Ohio Tripped, and Generation Tripped in South Central Michigan and Northern Ohio: 16:08:59 EDT to 16:10:27 EDT

5B) 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 a large power swing from Pennsylvania and New York through Ontario to Michigan

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

Figure 6.5. Line Flows Into Michigan



Note: These curves use data collected from the MECS Energy Management System, which records flow quantities every 2 seconds. As a result, the fast power swings that occurred between 16:10:36 to 16:13 were not captured by the recorders and are not reflected in these curves.

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 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 6.6).

The Galion-Ohio Central-Muskingum 345-kV line tripped first at Muskingum at 16:08:58.5 EDT on a phase-to-ground fault, reclosed and tripped again at 16:08:58.6 at Ohio Central, reclosed and tripped again at Muskingum on a Zone 3 relay, and finally tripped at Galion on a ground fault.

After the Galion-Ohio Central-Muskingum line outage and numerous 138-kV line trips in central Ohio, the East Lima-Fostoria Central 345-kV line tripped at 16:09:06 EDT on Zone 3 relay operation due to high current and extremely low voltage (80%). Investigation team modeling indicates that if automatic under-voltage load-shedding had been in place in northeast 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.

Recommendations
8, page 147; 21, page 158

Figure 6.7, a high-speed recording of 345-kV flows past Niagara Falls from the Hydro One recorders, shows the impact of the East Lima-Fostoria Central and the New York to Ontario power swing, which continued to oscillate for over 10 seconds. Looking at the MW flow line, it is clear that 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 returned to stability but continued to flutter until the Argenta-Battle Creek trip 90 seconds later. Voltages also began declining at this 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 (measured at the Michigan-Ontario border, and 437 MW at the Ontario-New York border at Niagara) 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.[2] 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 northwest Ohio transmission paths (above), and the stress that the still-high Cleveland, Toledo, and Detroit loads put onto the surviving lines and local generators.

Figure 6.7 also shows the magnitude of subsequent flows and voltages at the New York-Ontario Niagara border, triggered by the trips of the Argenta-Battle Creek, Argenta-Tompkins, Hampton-Pontiac and Thetford-Jewell 345-kV lines in Michigan, and the Erie West-Ashtabula-Perry

Figure 6.6. Ohio 345-kV Lines Trip, 16:08:59 to 16:09:07 EDT

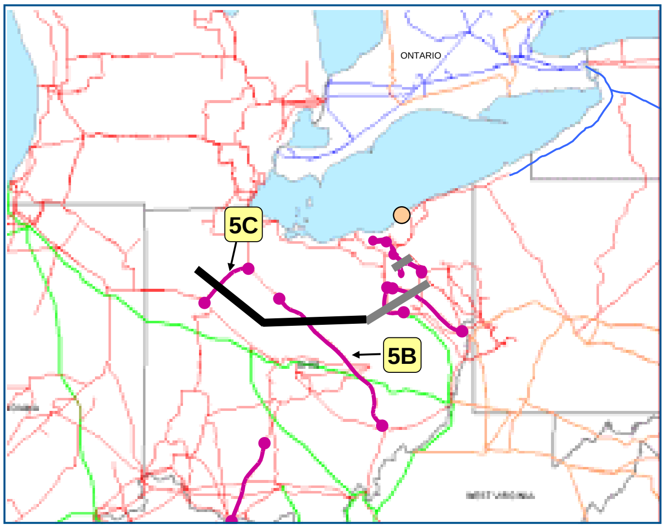
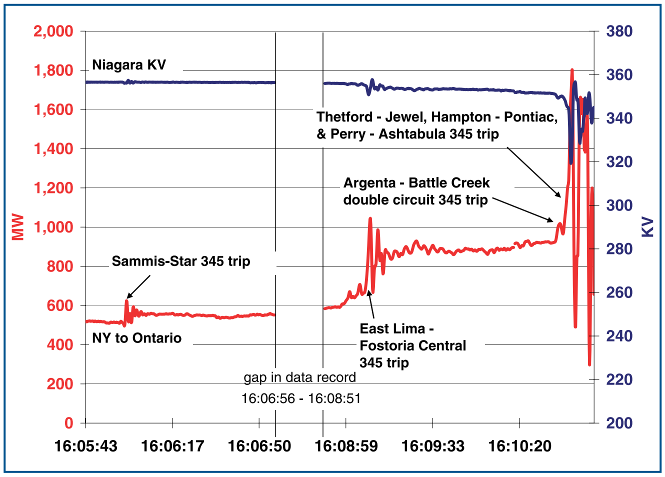


Figure 6.7. New York-Ontario Line Flows at Niagara



345-kV line linking the Cleveland area to Pennsylvania. Farther south, 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 synchronism 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.

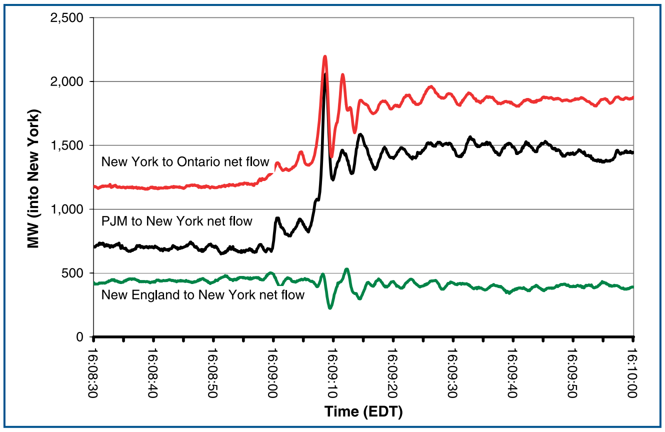
Figure 6.8, of metered power flows along the New York interfaces, documents how the flows heading north and west toward Detroit and Cleveland varied at different points on the grid. Beginning at 16:09:05 EDT, power flows jumped simultaneously across all three interfaces—but when the first power surge 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-NY and NY-Ontario interfaces because of the redistribution of flow around Lake Erie. The New England and Maritime 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, so that interface with New York 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. Transmission and generation facilities were then in a secure state across the NPCC region.

Zone 3 Relays and the Start of the Cascade

Zone 3 relays are set to provide breaker failure and relay backup for remote distance faults on a transmission line. If it senses a fault past the immediate reach of the line and its zone 1 and zone 2 settings, a zone 3 relay waits through a 1 to 2 second time delay to allow the primary line protection to act first. A few lines have zone 3 settings designed with overload margins close to the long-term emergency limit of the line, because the length and configuration of the line dictate a higher apparent impedance setting. Thus it is possible for a zone 3 relay to operate on line load or overload in extreme contingency conditions even in the absence of a fault (which is why many regions in the United States and Canada have eliminated the use of zone 3 relays on 230-kV and greater lines). Some transmission operators set zone 2 relays to serve the same purpose as zone 3s—i.e., to reach well beyond the length of the line it is protecting and protect against a distant fault on the outer lines.

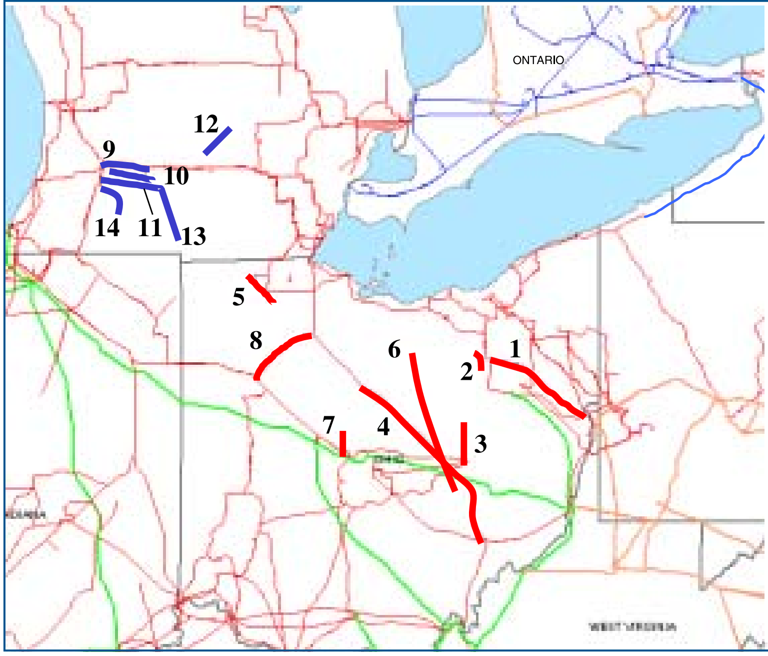
Figure 6.8. First Power Swing Has Varying Impacts Across the Grid



The Sammis-Star line tripped at 16:05:57 EDT on a zone 3 impedance relay although there were no faults occurring at the time, because increased real and reactive power flow caused the apparent impedance to be within the impedance circle (reach) of the relay. Between 16:06:01 and 16:10:38.6 EDT, thirteen more important 345 and 138-kV lines tripped on zone 3 operations that afternoon at the start of the cascade, including Galion-Ohio Central-Muskingum, East Lima-Fostoria Central, Argenta-Battle Creek, Argenta-Tompkins, Battle Creek-Oneida, and Perry-Ashtabula (Figure 6.9). These included several zone 2 relays in Michigan that had been set to operate like zone 3s, overreaching the line by more than 200% with no intentional time delay for remote breaker failure protection.[3] All of these relays operated according to their settings. However, the zone 3 relays (and zone 2 relays acting like zone 3s) acted so quickly that they impeded the natural ability of the electric system to hold together, and did not allow for any operator intervention to attempt to stop the spread of the cascade. The investigation team concluded that because these zone 2 and 3 relays tripped after each line overloaded, these relays were the common mode of failure that accelerated the geographic spread of the cascade. Given grid conditions and loads and the limited operator tools available, the speed of the zone 2 and 3 operations across Ohio and Michigan eliminated any possibility after 16:05:57 EDT that either operator action or automatic intervention could have limited or mitigated the growing cascade.

What might have happened on August 14 if these lines had not tripped on zone 2 and 3 relays? Each

Figure 6.9. Map of Zone 3 (and Zone 2s Operating Like Zone 3s) Relay Operations on August 14, 2003



	Zone 3 Tripped Lines	State	Trip Time (EDT)
1	Sammis - Star (345 kV)	Ohio	16:05:57.504
2	Star (138/69 kV) Transformer # 6 Star - Dale (69kV)	Ohio	16:06:01
3	Ohio CTL - Wooster (138 kV)	Ohio	16:08:58
4	Galion - Ohio CTL - Muskingum (345 kV) @ Muskingum	Ohio	16:08:59.158
5	Richland - Wauseon - Midway (138 kV)	Ohio	16:09:00
6	Academia - Howard (138 kV) Philo - Howard (138 kV)	Ohio	16:09:05
7	Tangy - Kirby (138 kV) Tangy - Crissinger (138 kV)	Ohio	16:09:06
8	E. Lima - Fostoria (345 kV)	Ohio	16:09:06.311
9	Argenta - Battle Ck (345 kV)	Michigan	16:10:36.230
10	Argenta - Tompkins (345 kV) Battle Ck - Oneida	Michigan	16:10:36.310
11	Argenta - Verona (138 kV)	Michigan	16:10:37.550
12	Delhi - Island Road (138 kV)	Michigan	16:10:37.870
13	Verona - Batavia (138 kV)	Michigan	16:10:37.900
14	Argenta - Morrow (138 kV)	Michigan	16:10:38.350

Voltage Collapse

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 dropping voltage, 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, all 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 they were just sufficient to supply the reactive power demand in the area and maintain stable albeit depressed voltages for the outage conditions experienced.

But the lines in the Cleveland-Akron area tripped as a result of tree contacts well below the nominal rating of the lines and **not due to low voltages**, which is a precursor for voltage collapse. The initial trips within FirstEnergy began because of ground faults with untrimmed trees, not because of a shortage of reactive power and low voltages. Voltage levels were within workable bounds before individual transmission trips began, and those trips occurred within normal line ratings rather than in overloads. 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)—but it stabilized after each line trip until the next circuit trip. Soon northern Ohio lines began to trip out automatically on protection from overloads, not from insufficient reactive power. Once several lines tripped in the Cleveland-Akron area, the power flow was rerouted to other heavily loaded lines in northern Ohio, causing depressed voltages which led to automatic tripping on protection from overloads. Voltage collapse therefore was not a cause of the cascade.

As the cascade progressed beyond Ohio, it spread due not to insufficient reactive power and a voltage collapse, but because of dynamic power swings and the resulting system instability. Figure 6.7 shows voltage levels recorded at the Niagara area. It shows clearly that voltage levels remained stable until 16:10:30 EDT, despite significant power fluctuations. In the cascade that followed, the voltage instability was a companion to, not a driver of, the angle instability that tripped generators and lines.

was operating with high load, and loads on each line grew as each preceding line tripped out of service. But if these lines had not tripped quickly on zone 2s and 3s, each might have remained heavily loaded, with conductor temperatures increasing, for as long as 20 to 30 minutes before the line sagged into something and experienced a ground fault. For instance, the Dale-West Canton line took 20 minutes to trip under 160 to 180% of its normal rated load. Even with sophisticated modeling it is impossible to predict just how long this delay might have occurred (affected by wind speeds, line loadings, and line length, tension and ground clearance along every span), because the system did not become dynamically unstable until at least after the Thetford-Jewell trip at 16:10:38 EDT. During this period the system would likely have remained stable and been able to readjust after each line trip on ground fault. If this period of deterioration and overloading under stable conditions had lasted for as little as 15 minutes or as long as an hour, it is possible that the growing problems could have been recognized and action taken, such as automatic under-voltage load-shedding, manual load-shedding in Ohio or other measures. So although the operation of zone 2 and 3 relays in Ohio and Michigan did not cause the blackout, it is certain that they greatly expanded and accelerated the spread of the cascade.

Recommendation
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5D) Multiple Power Plants Tripped, Totaling 946 MW: 16:09:08 to 16:10:27 EDT

16:09:08 EDT: Michigan Cogeneration Venture plant reduction of 300 MW (from 1,263 MW to 963 MW)

16:09:17 EDT: Avon Lake 7 unit trips (82 MW)

16:09:17 EDT: Burger 3, 4, and 5 units trip (355 MW total)

16:09:30 EDT: Kinder Morgan units 3, 6 and 7 trip (209 MW total)

The Burger units tripped after the 138-kV lines into the Burger 138-kV substation (Ohio) tripped from the low voltages in the Cleveland area (Figure 6.10). The MCV plant is in central Michigan. Kinder Morgan is in south-central Michigan. The Kinder-Morgan units tripped due to a transformer fault and one due to 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.

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 northeastern United States and the province of Ontario were 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 to 16:10:39 EDT

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

16:10:36.2 EDT: Argenta-Battle Creek 345-kV line tripped

16:10:36.3 EDT: Argenta-Tompkins 345-kV line tripped

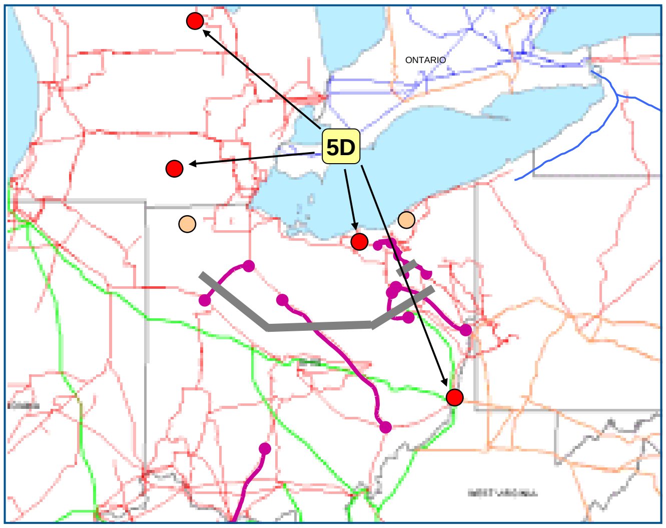
16:10:36.8 EDT: Battle Creek-Oneida 345-kV line tripped

16:10:37 EDT: Sumpter Units 1, 2, 3, and 4 units tripped on under-voltage (300 MW near Detroit)

16:10:37.5 EDT: MCV Plant output dropped from 963 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 generation units tripped in response to

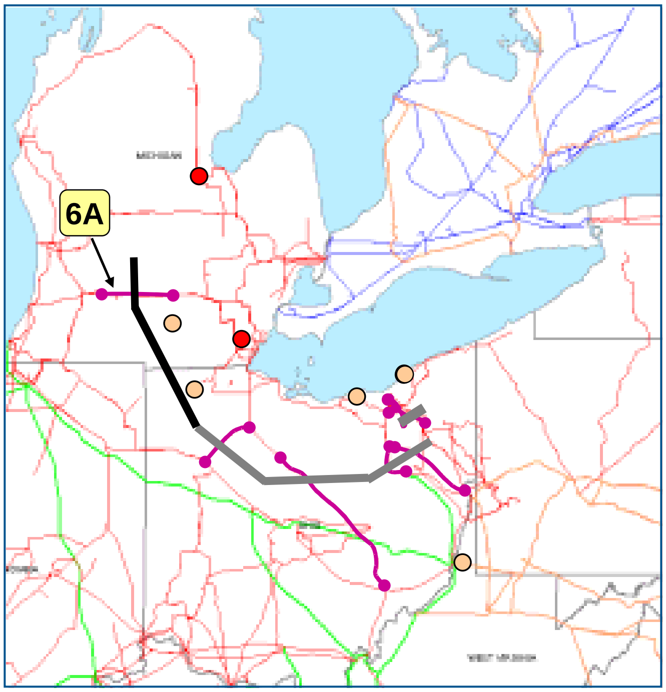
Figure 6.10. Michigan and Ohio Power Plants Trip



under-voltage on the system. Michigan lines west of Detroit then began to trip, as shown in Figure 6.11.

The Argenta-Battle Creek relay first opened the line at 16:10:36.230 EDT, reclosed it 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 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 when 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 the second breaker only when the two ends 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 70º difference in phase across the circuit breaker reclosing the line. There is no evidence that the reclose caused harm to the local generators.

Figure 6.11. Transmission and Generation Trips in Michigan, 16:10:36 to 16:10:37 EDT



6B) Western and Eastern Michigan separation started: 16:10:37 EDT to 16:10:38 EDT

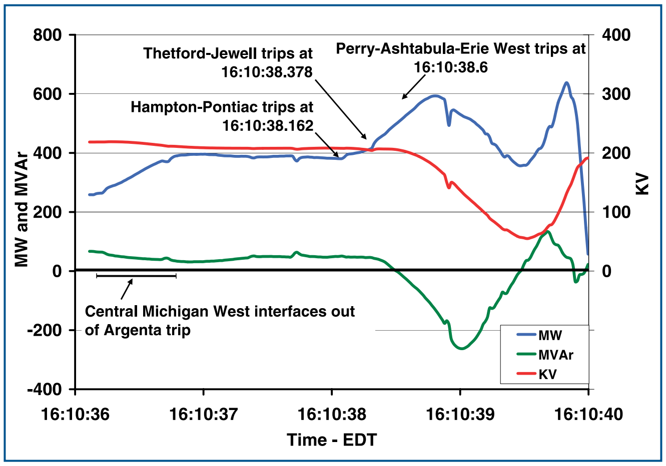
16:10:38.2 EDT: Hampton-Pontiac 345-kV line tripped

16:10:38.4 EDT: Thetford-Jewell 345-kV line tripped

After the Argenta lines tripped, the phase angle between eastern and western Michigan began to increase. The Hampton-Pontiac and Thetford-Jewell 345-kV lines were the only lines remaining connecting Detroit to power sources and 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 northwest Pennsylvania. These trips completed the extra-high voltage network separation between eastern and western Michigan.

The Power System Disturbance Recorders at Keith and Lambton, Ontario, captured these events in the flows across the Ontario-Michigan interface, as shown in Figure 6.12 and Figure 6.16. It shows clearly that the west to east Michigan separation (the Thetford-Jewell trip) was the start and Erie West-Ashtabula-Perry was the trigger for the 3,700 MW 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 draw power from the northeast instead. To the south,

Figure 6.12. Flows on Keith-Waterman 230-kV Ontario-Michigan Tie Line



Erie West-Ashtabula-Perry was the last 345-kV eastern link 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 counter-clockwise direction around Lake Erie through the single path left in eastern Michigan, pulling power out of Ontario, New York and PJM.

Figures 6.13 and 6.14 show the results of investigation team modeling of the line loadings on the Ohio, Michigan, and other regional interfaces for the period between 16:05:57 until the Thetford-Jewell trip, to understand how power flows shifted during this period. The team simulated evolving system conditions on August 14, 2003, based on the 16:05:50 power flow case developed by the MAAC-ECAR-NPCC Operations Studies Working Group. Each horizontal line in the graph indicates a single or set of 345-kV lines and its loading as a function of normal ratings over time as first one, then another, set of circuits tripped out of service. In general, each subsequent line trip causes the remaining line loadings to rise; where a line drops (as Erie West-Ashtabula-Perry in Figure 6.13 after the Hanna-Juniper trip), that indicates that line loading lightened, most likely due to customers dropped from service. Note that Muskingum and East Lima-Fostoria Central were overloaded before they tripped, but the Michigan west and north interfaces were not overloaded before they tripped. Erie West-Ashtabula-Perry was loaded to 130% after the Hampton-Pontiac and Thetford-Jewell trips.

The Regional Interface Loadings graph (Figure 6.14) shows that loadings at the interfaces between PJM-NY, NY-Ontario and NY-New England were well within normal ratings before the east-west Michigan separation.

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

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

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.

Perry-Ashtabula was the last 345-kV line connecting northern Ohio to the east south of Lake Erie. This line's trip at the Perry substation on a zone 3 relay operation separated the northern Ohio 345-kV transmission system from Pennsylvania and all eastern 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 at the interface between the Michigan and Ontario systems (Figure 6.15). 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 EDT under-frequency load shedding in the Cleveland area interrupted about 1,750 MW of load. However, the load shedding did not drop enough load relative to local generation to rebalance and arrest the frequency decline. Since the electrical system always seeks to balance load and generation, the high loads in Detroit and Cleveland drew power over the only major transmission path remaining—the lines from eastern Michigan into Ontario. Mismatches between generation and load are reflected in changes in frequency, so with more generation than load frequency rises and with less generation than load, frequency falls.

Figure 6.13. Simulated 345-kV Line Loadings from 16:05:57 through 16:10:38.4 EDT

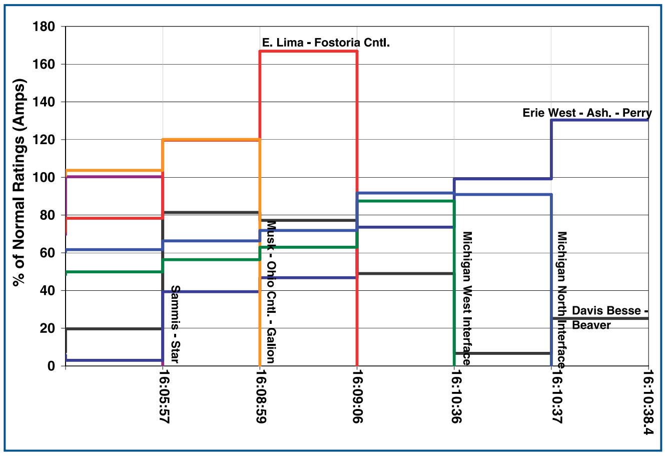
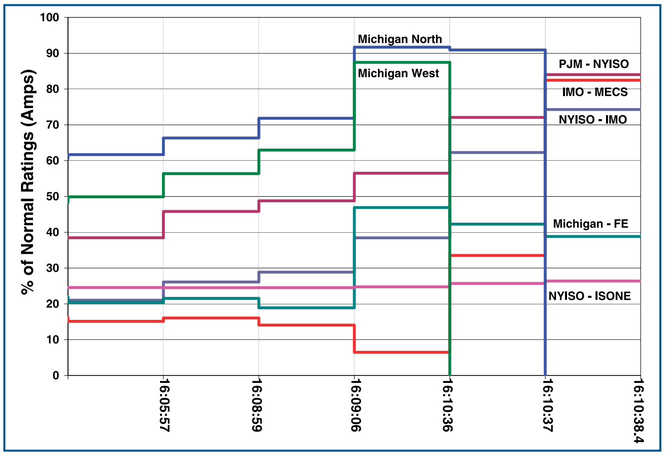


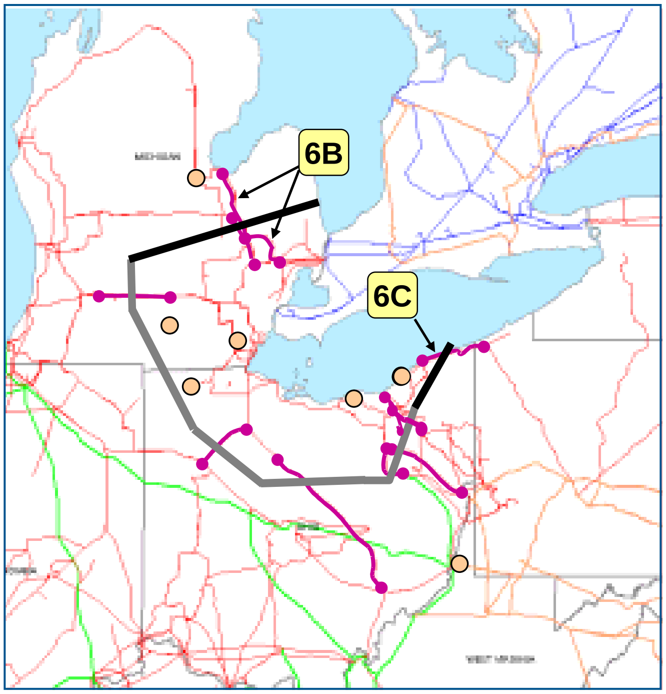
Figure 6.14. Simulated Regional Interface Loadings from 16:05:57 through 16:10:38.4 EDT



At 16:10:38.6 EDT, after the above transmission paths into Michigan and Ohio failed, 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 EDT, with this new surge they peaked at 3,700 MW at 16:10:39 EDT (Figure 6.16). Electricity moved along a giant loop 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 drastically lowered voltage and increased current levels on the transmission lines along the Pennsylvania-New York transmission interface.

This was a power surge of large magnitude, so frequency was not the same across the Eastern Interconnection. As Figure 6.16 shows, 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. Detroit would soon lose synchronism and black out (as evidenced by the rapid power oscillations decaying after 16:10:43 EDT).

Figure 6.15. Michigan Lines Trip and Ohio Separates from Pennsylvania, 16:10:36 to 16:10:38.6 EDT



Modeling the Cascade

Computer modeling of the cascade built upon the modeling conducted of the pre-cascade system conditions described in Chapter 5. That earlier modeling developed steady-state load flow and voltage analyses for the entire Eastern Interconnection from 15:00 to 16:05:50 EDT. The dynamic modeling used the steady state load flow model for 16:05:50 as the starting point to simulate the cascade. Dynamic modeling conducts a series of load flow analyses, moving from one set of system conditions to another in steps one-quarter of a cycle long—in other words, to move one second from 16:10:00 to 16:10:01 requires simulation of 240 separate time slices.

The model used a set of equations that incorporate the physics of an electrical system. It contained detailed sub-models to reflect the characteristics of loads, under-frequency load-shedding, protective relay operations, generator operations (including excitation systems and governors), static VAr compensators and other FACTS devices, and transformer tap changers.

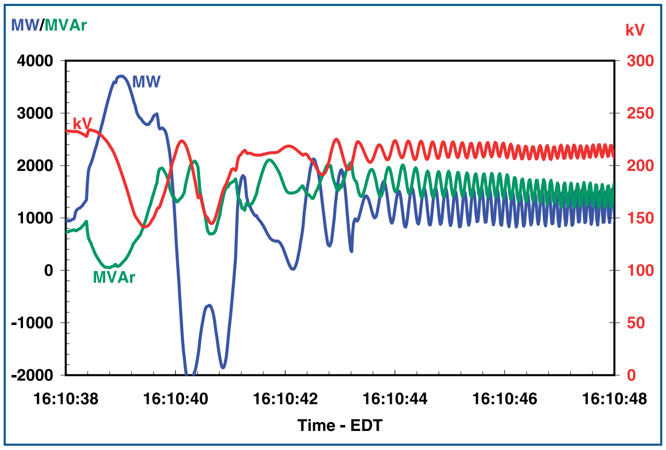
The modelers compared model results at each moment to actual system data for that moment to verify a close correspondence for line flows and voltages. If there was too much of a gap between modeled and actual results, they looked at the timing of key events to see whether actual data might have been mis-recorded, or whether the modeled variance for an event not previously recognized as significant might influence the outcome. Through 16:10:40 EDT, the team achieved very close benchmarking of the model against actual results.

The modeling team consisted of industry members from across the Midwest, Mid-Atlantic and NPCC areas. All have extensive electrical engineering and/or mathematical training and experience as system planners for short- or long-term operations.

This modeling allows the team to verify its hypotheses as to why particular events occurred and the relationships between different events over time. It allows testing of many “what if” scenarios and alternatives, to determine whether a change in system conditions might have produced a different outcome.

Just before the Argenta-Battle Creek trip, when Michigan separated west to east at 16:10:37 EDT, almost all of the generators in the eastern interconnection were moving in synchronism with the overall grid frequency of 60 Hertz (shown at the bottom of Figure 6.17), but when the swing started, those machines absorbed some of its energy as they attempted to adjust and resynchronize with the rapidly changing frequency. In many cases, this adjustment was unsuccessful and the generators tripped out from milliseconds to several seconds thereafter.

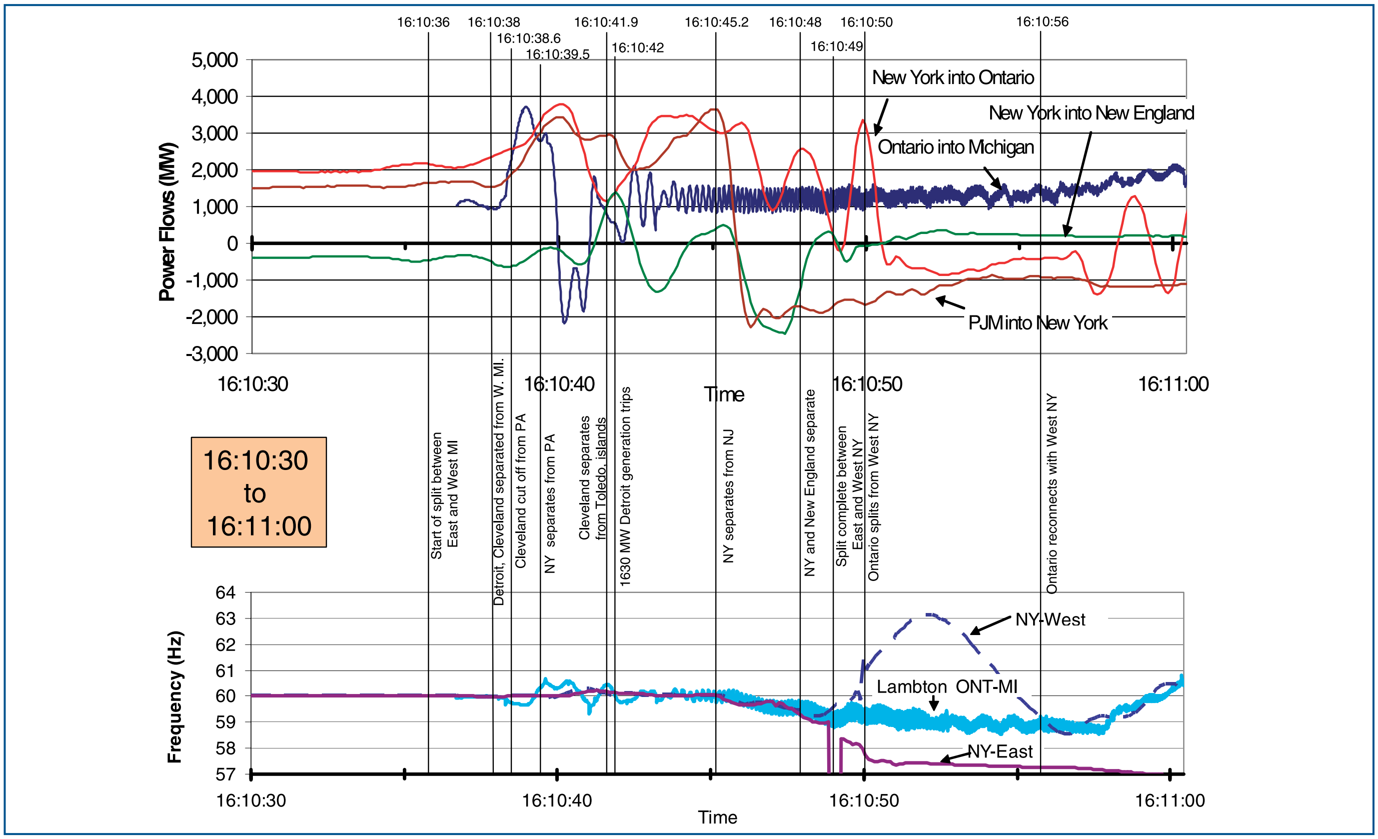
Figure 6.16. Active and Reactive Power and Voltage from Ontario into Detroit



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. Between 16:10:38 and 16:10:41 EDT, the power swings caused a sudden extraordinary 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 6.17 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 clearly 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 to complete the path across

Figure 6.17. Measured Power Flows and Frequency Across Regional Interfaces, 16:10:30 to 16:11:00 EDT, with Key Events in the Cascade



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.

After Cleveland was cut off from Pennsylvania and eastern power sources, Figure 6.17 shows the start of the dynamic power swing at 16:10:38.6. Because the loads of Cleveland, Toledo and Detroit (less the load already blacked out) were now hanging off Michigan and Ontario, this forced a gigantic shift in power flows to meet that demand. As noted above, flows from Ontario into Michigan increased from 1,000 MW to 3,700 MW shortly after the start of the swing, while flows from PJM into New York were close behind. But within two seconds from the start of the swing, at 16:10:40 EDT flows reversed and coursed back from Michigan into Ontario at the same time that frequency at the interface dropped, indicating that significant generation had been lost. Flows that had been westbound across the Ontario-Michigan interface by over 3,700 MW at 16:10:38.8 dropped down to 2,100 MW eastbound by 16:10:40, and then returned westbound starting at 16:10:40.5.

A series of circuits tripped along the border between PJM and the NYISO due to zone 1 impedance relay operations on overload and depressed voltage. 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.

6D) 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

Line trips in Ohio and eastern Michigan:

16:10:39.5 EDT: Bay Shore-Monroe 345-kV line

16:10:39.6 EDT: Allen Junction-Majestic-Monroe 345-kV line

16:10:40.0 EDT: Majestic-Lemoyne 345-kV line

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

16:10:41.8 EDT: Fostoria Central-Galion 345-kV line

16:10:41.911 EDT: Beaver-Davis Besse 345-kV line

Under-frequency load-shedding in Ohio:

FirstEnergy shed 1,754 MVA load

AEP shed 133 MVA load

Seven power plants, for a total of 3,294 MW of generation, tripped off-line in Ohio:

16:10:42 EDT: Bay Shore Units 1-4 (551 MW near Toledo) tripped on over-excitation

16:10:40 EDT: Lakeshore unit 18 (156 MW, near Cleveland) tripped on under-frequency

16:10:41.7 EDT: Eastlake 1, 2, and 3 units (304 MW total, near Cleveland) tripped on under-frequency

16:10:41.7 EDT: Avon Lake unit 9 (580 MW, near Cleveland) tripped on under-frequency

16:10:41.7 EDT: Perry 1 nuclear unit (1,223 MW, near Cleveland) tripped on under-frequency

16:10:42 EDT: Ashtabula unit 5 (184 MW, near Cleveland) tripped on under-frequency

16:10:43 EDT: West Lorain units (296 MW) tripped on under-voltage

Four power plants producing 1,759 MW tripped off-line near Detroit:

16:10:42 EDT: Greenwood unit 1 tripped (253 MW) on low voltage, high current

16:10:41 EDT: Belle River unit 1 tripped (637 MW) on out-of-step

16:10:41 EDT: St. Clair unit 7 tripped (221 MW, DTE unit) on high voltage

16:10:42 EDT: Trenton Channel units 7A, 8 and 9 tripped (648 MW)

Back 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 (Figure 6.18). Frequency in this large 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. When the Beaver-Davis Besse 345-kV line between Cleveland and Toledo tripped, it left the Cleveland area completely isolated and area frequency rapidly declined. 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. 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 in Ohio on Lake Erie, not far from the Pennsylvania border. The Perry plant was inside a decaying electrical island, and the plant tripped on under-frequency, as designed. A number of other units near Cleveland tripped off-line by under-frequency protection.

The tremendous power flow into Michigan, beginning at 16:10:38, occurred when Toledo and Cleveland were still connected to the grid only through Detroit. After the Bay Shore-Monroe line tripped at 16:10:39, Toledo-Cleveland were separated into their own island, dropping a large amount of load off the Detroit system. This left Detroit suddenly with excess generation, much of which was greatly accelerated in angle as the depressed voltage in Detroit (caused by the high demand in Cleveland) caused the Detroit units to pull nearly out of step. With the Detroit generators running at maximum mechanical output, they began to pull out of synchronous operation with the rest of the grid. When voltage in Detroit returned to near-normal, the generators 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 6.19, 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 tripped in response. After formation of the Cleveland-Toledo island at 16:10:40 EDT, Detroit frequency spiked to almost 61.7 Hz before dropping, momentarily equalized between the Detroit and Ontario systems, but Detroit frequency began to decay at 2 Hz/sec and the generators then experienced under-speed conditions.

Re-examination of Figure 6.17 shows the power swing from the northeast through Ontario into Michigan and northern Ohio that began at 16:10:37, and how it reverses and swings back around Lake Erie at 16:10:39 EDT. That return was caused by the combination of natural oscillations, 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 EDT. Since the system was now fully dynamic, this large oscillation eastbound would lead naturally to a rebound, which began at 16:10:40 EDT with an inflection point reflecting generation shifts between Michigan and Ontario and additional line losses in Ohio.

Figure 6.18. Cleveland and Toledo Islanded, 16:10:39 to 16:10:46 EDT

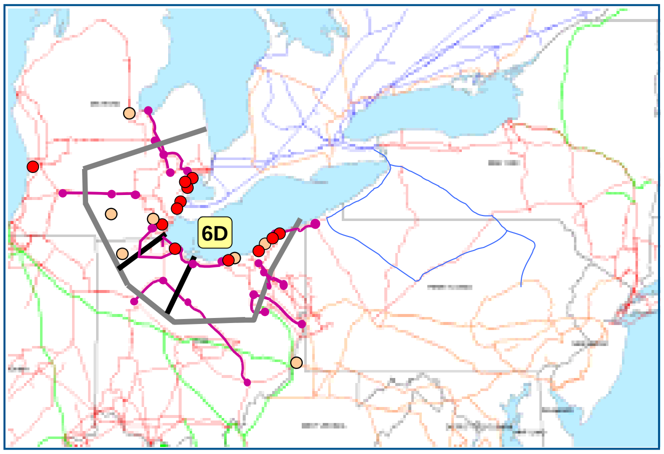
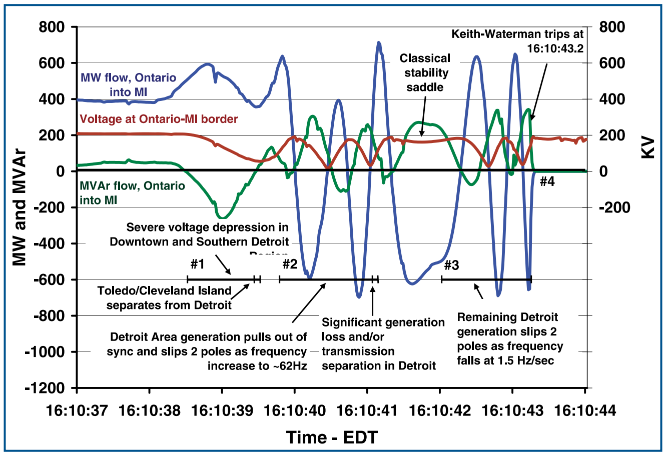


Figure 6.19. Generators Under Stress in Detroit, as Seen from Keith PSDR



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

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

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

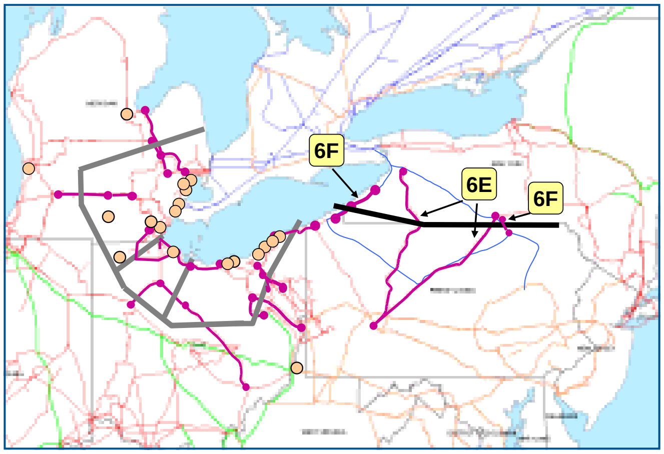
6F) 16:10:44 EDT: South Ripley-Erie East 230 kV, and South Ripley-Dunkirk 230 kV

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

Responding to the swing of power out of Michigan toward Ontario and into New York and PJM, zone 1 relays on the 345-kV lines separated Pennsylvania from New York (Figure 6.20). Homer City-Watercure (177 miles or 285 km) and Homer City-Stolle Road (207 miles or 333 km) are very long lines and so have high impedance. Zone 1 relays do not have timers, and operate instantly when a power swing enters the relay target circle. For normal length lines, zone 1 relays have small target circles because the relay is measuring a less than the full length of the line—but for a long line the large line impedance enlarges the relay's 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 early in the face of such large power swings. Most of the other interfaces between regions are on short ties—for instance, the ties between New York and Ontario and Ontario to Michigan are only about 2 miles (3.2 km) 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 for a short line covers a small area so a power swing is less likely to enter the relay target circle at all, averting a zone 1 trip.

Figure 6.20. Western Pennsylvania Separates from New York, 16:10:39 EDT to 16:10:44 EDT



At 16:10:44 EDT, 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 northeast 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) buffered 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.

6G) Transmission paths disconnected in New Jersey and northern Ontario, isolating the northeast portion of the Eastern Interconnection: 16:10:43 to 16:10:45 EDT

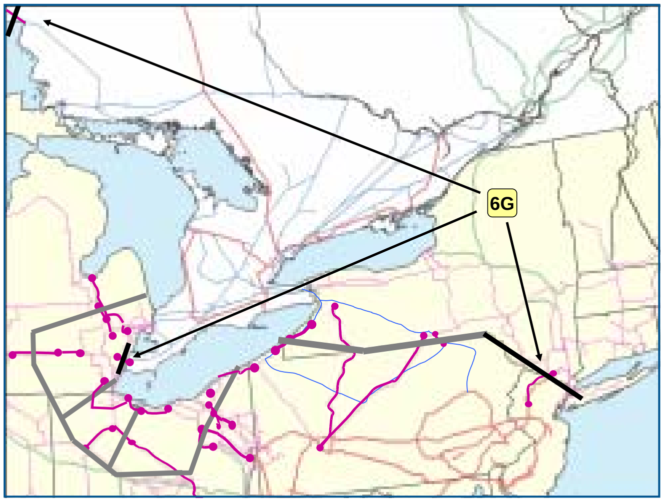
16:10:43 EDT: Keith-Waterman 230-kV line tripped

16:10:45 EDT: Wawa-Marathon 230-kV lines tripped

16:10:45 EDT: Branchburg-Ramapo 500-kV line tripped

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 6.21). This put more power onto the remaining interface between Ontario and Michigan, but

Figure 6.21. Northeast Separates from Eastern Interconnection, 16:10:45 EDT



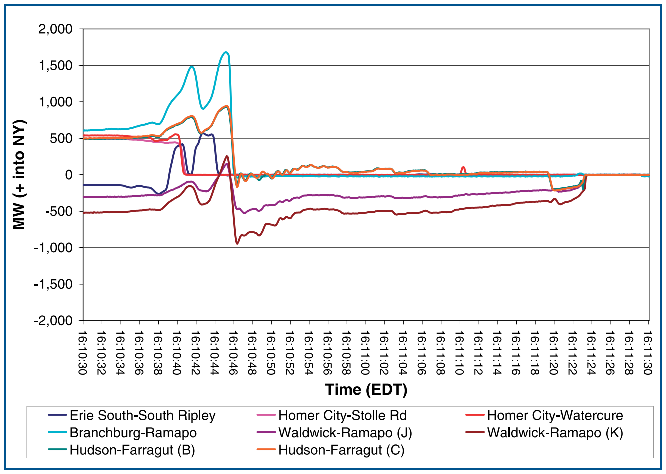
triggered sustained oscillations in both power flow and frequency along the remaining 230-kV line.

At 16:10:45 EDT, northwest Ontario separated from the rest of Ontario when the Wawa-Marathon 230-kV lines (104 miles or 168 km long) 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.

The 69-mile (111 km) long Branchburg-Ramapo 500-kV 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. Figure 6.22 shows how that line disconnected at 16:10:45 EDT, along with other underlying 230 and 138-kV lines in northeast New Jersey. Branchburg–Ramapo was carrying over 3,000 MVA and 4,500 amps with voltage at 79% 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 notably 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 northeast 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.

Figure 6.22. PJM to New York Interties Disconnect



Note: The data in this figure come from the NYISO Energy Management System SDAC high speed analog system, which records 10 samples per second.

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 they were designed to. No human intervention occurred by operators at PJM headquarters or elsewhere to effect this split. 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 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. Frequency in the Eastern Interconnection was 60.3 Hz at the time of separation; this means that approximately 3,700 MW of excess generation that was on-line to export into the northeast was now in the main Eastern Island, separated from the load it had been serving. This left the northeast island with even less in-island generation on-line as it attempted to rebalance in the next phase of the cascade.

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

Overview of This Phase

During the next 3 seconds, the islanded northern section of the Eastern Interconnection broke apart internally. Figure 6.23 illustrates the events of this phase.

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

7B) New York transmission system split along Total East interface: 16:10:49 EDT

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

By this point most portions of the affected area were blacked out.

If the 6th phase of the cascade was about dynamic system oscillations, the last phase is a story of the search for balance between loads and generation. Here it is necessary to understand three matters related to system protection—why the blackout stopped where it did, how and why under-voltage and under-frequency load-shedding work, and what happened to the generators on August 14 and why. These matter because loads and generation must ultimately balance in real-time to remain stable. When the grid is breaking apart into islands, if generators stay on-line longer, then the better the chances to keep the lights on within each island and restore service following a blackout; so automatic load-shedding, transmission relay protections and generator protections must avoid premature tripping. They must all be coordinated to reduce the likelihood of system break-up, and once break-up occurs, to maximize an island's chances for electrical survival.

Why the Blackout Stopped Where It Did

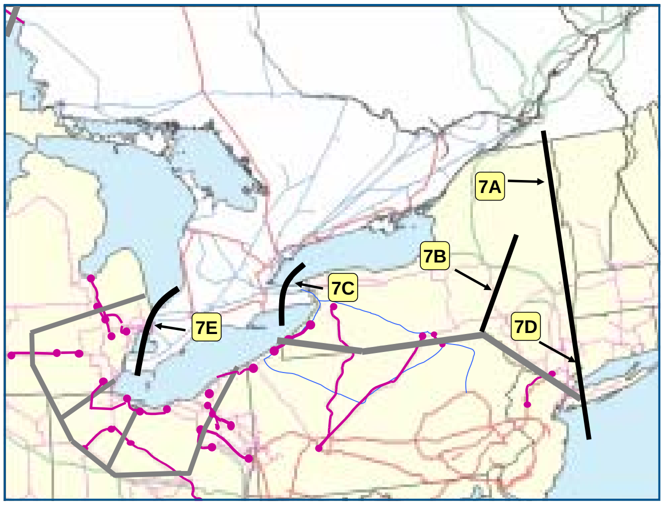
Extreme system conditions can damage equipment in several ways, from melting aluminum conductors (excessive currents) to breaking turbine blades on a generator (frequency excursions). The power system is designed to ensure that if conditions on the grid (excessive or inadequate voltage, apparent impedance 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. This protective measure leaves the generator in good condition to help rebuild the system once a blackout is over and restoration begins. When unstable power swings develop between a group of generators that are losing synchronization (unable to match frequency) with the rest of the system, one effective way to stop the oscillations is to stop the flows entirely by disconnecting the unstable generators from 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 critical levels and harms the generator or the system.

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 with relay settings using longer apparent impedance tripping zones and normal time settings. 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

Figure 6.23. New York and New England Separate, Multiple Islands Form



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 a massive power surge caused each line to trip. To the relays, this power surge altered the voltages and currents enough that they appeared to be faults. The power surge was caused by power flowing to those areas that were generation-deficient (Cleveland, Toledo and Detroit) or rebounding back. 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 were generation-deficient.

Protective relay settings on transmission lines operated as they were designed and set to behave on August 14. In some cases line relays did not trip in the path of a power surge because the apparent impedance on the line was not low enough—not because of the magnitude of the current, but rather because voltage on that line was high enough that the resulting impedance was adequate to avoid entering the relay's target zone. Thus relative voltage levels across the northeast also affected which areas blacked out and which areas stayed on-line.

In the U.S. Midwest, 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 readily available to help buffer their areas against potential voltage collapse without widespread generation trips.

The investigation team has used simulation to examine whether special protection schemes, designed to detect an impending cascade and separate the grid at specific interfaces, could have been or should be set up to stop a power surge and prevent it from sweeping through an interconnection and causing the breadth of line and generator trips and islanding that occurred that day. The team has concluded that such schemes would have been ineffective on August 14.

Under-Frequency and Under-Voltage Load-Shedding

Automatic load-shedding measures are designed into the electrical system to operate as a last resort, under the theory that it is wise to shed some load in a controlled fashion if it can forestall the loss of a great deal of load to an uncontrollable cause. Thus there are two kinds of automatic load-shedding installed in North America—under-voltage load-shedding, which sheds load to prevent local area voltage collapse, and under-frequency load-shedding, which is designed to rebalance load and generation within an electrical island once it has been created by a system disturbance.

Automatic under-voltage load-shedding (UVLS) responds directly to voltage conditions in a local area. UVLS drops several hundred MW of load in pre-selected blocks within urban load centers, triggered in stages when local voltage drops to a designated level—likely 89 to 92% or even higher—with a several second delay. The goal of a UVLS scheme is to eliminate load in order to restore reactive power relative to demand, to prevent voltage collapse and contain a voltage problem within a local area rather than allowing it to spread in geography and magnitude. If the first load-shed step does not allow the system to rebalance, and voltage continues to deteriorate, then the next block of UVLS is dropped. Use of UVLS is not mandatory, but is done at the option of the control area and/or reliability council. UVLS schemes and trigger points should be designed to respect the local area's system vulnerabilities, based on voltage collapse studies. As noted in Chapter 4, there is no UVLS system in place within Cleveland and Akron; had such a scheme been implemented before August, 2003, shedding 1,500 MW of load in that area before the loss of the Sammis-Star line might have prevented the cascade and blackout.

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In contrast to UVLS, automatic under-frequency load-shedding (UFLS) is designed for use in extreme conditions to stabilize the balance between generation and load after an electrical island has been formed, dropping enough load to allow frequency to stabilize within the island. All synchronous generators in North America are designed to operate at 60 cycles per second

(Hertz) and frequency reflects how well load and generation are balanced—if there is more load than generation at any moment, frequency drops below 60 Hz, and it rises above that level if there is more generation than load. By dropping load to match available generation within the island, UFLS is a safety net that helps to prevent the complete blackout of the island, which allows faster system restoration afterward. UFLS is not effective if there is electrical instability or voltage collapse within the island.

Today, UFLS installation is a NERC requirement, designed to shed at least 25-30% of the load in steps within each reliability coordinator region. 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 59.3 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 generators could be damaged (see Figure 2.4).

In NPCC, following the Northeast blackout of 1965, the region adopted automatic under-frequency load-shedding criteria and manual load-shedding within ten minutes to prevent a recurrence of the cascade and better protect system equipment from damage due to a high-speed system collapse. Under-frequency load-shedding triggers vary by regional reliability council—New York and all of the Northeast Power Coordinating Council, plus the Mid-Atlantic Area Council use 59.3 Hz as the first step for UFLS, while ECAR uses 59.5 Hz as their first step for UFLS.

The following automatic UFLS operated on the afternoon of August 14:

- Ohio shed over 1,883 MVA beginning at 16:10:39 EDT
- Michigan shed a total of 2,835 MW
- New York shed a total of 10,648 MW in numerous steps, beginning at 16:10:48
- PJM shed a total of 1,324 MVA in 3 steps in northern New Jersey beginning at 16:10:48 EDT
- Ontario shed a total of 7,800 MW in 2 steps, beginning at 16:10:4
- New England shed a total of 1,098 MW.

It must be emphasized that the entire northeast system was experiencing large scale, dynamic oscillations in 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.

Why the Generators Tripped Off

At least 265 power plants with more than 508 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 Québec, 5 plants (all isolated onto the Ontario system)[4]
- Ontario, 92 plants
- ISO-New England, 31 plants
- MISO, 32 plants
- New York ISO, 70 plants
- PJM, 35 plants

By type:

- Conventional steam units, 66 plants (37 coal)
- Combustion turbines, 70 plants (37 combined cycle)
- Nuclear, 10 plants—7 U.S. and 3 Canadian, totaling 19 units (the nuclear unit outages are discussed in Chapter 8)
- Hydro, 101
- Other, 18.

Within the overall cascade sequence, 29 (6%) generators tripped between the start of the cascade at 16:05:57 (the Sammis-Star trip) and the split between Ohio and Pennsylvania at 16:10:38.6 EDT (Erie West-Ashtabula-Perry), which triggered the first big power swing. These trips were caused by the generators' protective relays responding to overloaded transmission lines, so many of these trips were reported as under-voltage or over-current. The next interval in the cascade was as the portions of the grid lost synchronism, from 16:10:38.6 until 16:10:45.2 EDT, when Michigan-New York-Ontario-New England separated from the rest of the Eastern Interconnection. Fifty more generators (10%) tripped as the islands formed, particularly due to changes in configuration, loss of synchronism, excitation system failures, with some under-frequency and under-voltage. In the third phase of generator losses, 431 generators (84%) tripped after the islands formed, many at the same time that under-frequency load-shedding was occurring. This is illustrated in Figure 6.24. It is worth noting, however, that many generators did not trip instantly after the trigger condition that led to the trip—rather, many relay protective devices operate on time delays of milliseconds to seconds in duration, so that a generator that reported tripping at 16:10:43 on under-voltage or “generator protection” might have experienced the trigger for that condition several seconds earlier.

The high number of generators that tripped before formation of the islands helps to explain why so much of the northeast blacked out on August 14—many generators had pre-designed protection points that shut the unit down early in the cascade, so there were fewer units on-line to prevent island formation or to maintain balance between load and supply within each island after it formed. In particular, it appears that some generators tripped to protect the units from conditions that did not justify their protection, and many others were set to trip in ways that were not coordinated with the region’s under-frequency load-shedding, rendering that UFLS scheme less effective. Both factors compromised successful islanding and precipitated the blackouts in Ontario and New York.

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Most of the unit separations fell in the 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.

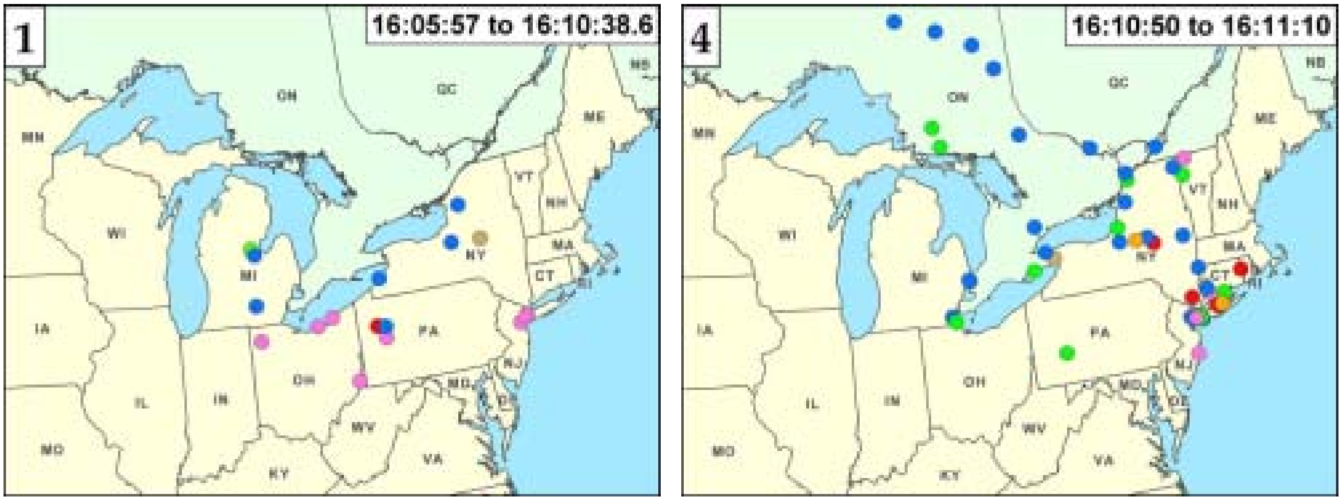
The large power swings and excursions of system frequency put all the units in their path through a sequence of major disturbances that shocked several units into tripping. Plant controls had actuated fast governor action on several of these to turn back the throttle, then turn it forward, only to turn it back again as some frequencies changed several times by as much as 3 Hz (about 100 times normal deviations). Figure 6.25 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. This also illustrates the time lag between system events and the generator reaction—this generator was first disturbed by system conditions at 16:10:37, but did not trip until 16:11:47, over a minute later.

Under-frequency (10% of the generators reporting) and under-voltage (6%) trips both reflect responses to system conditions. Although combustion turbines in particular are designed with under-voltage relay protection, it is not clear why this is needed. An under-voltage condition by itself and over a set time period may not necessarily be a generator hazard (although it could affect plant auxiliary systems). Some generator under-voltage relays were set to trip at or above 90% voltage. However, a motor stalls out at about 70% voltage and a motor starter contactor drops out around 75%, so if there is a compelling need to protect the turbine from the system the under-voltage trigger point should be no higher than 80%.

An excitation failure is closely related to a voltage trip. As local voltages decreased, so did frequency. Over-excitation operates on a calculation of volts/hertz, so as frequency declines faster than voltage over-excitation relays would operate. It is not clear that these relays were coordinated with each machine’s exciter controls, to be sure that it was protecting the machine for the proper range of its control capabilities. Large units have two relays to detect volts/Hz—one at the generator and one at the transformer, each with a slightly different volts/Hz setting and time delay. It is possible that these settings can cause a generator to trip within a generation-deficient island as frequency is attempting to rebalance, so these settings should be carefully evaluated.

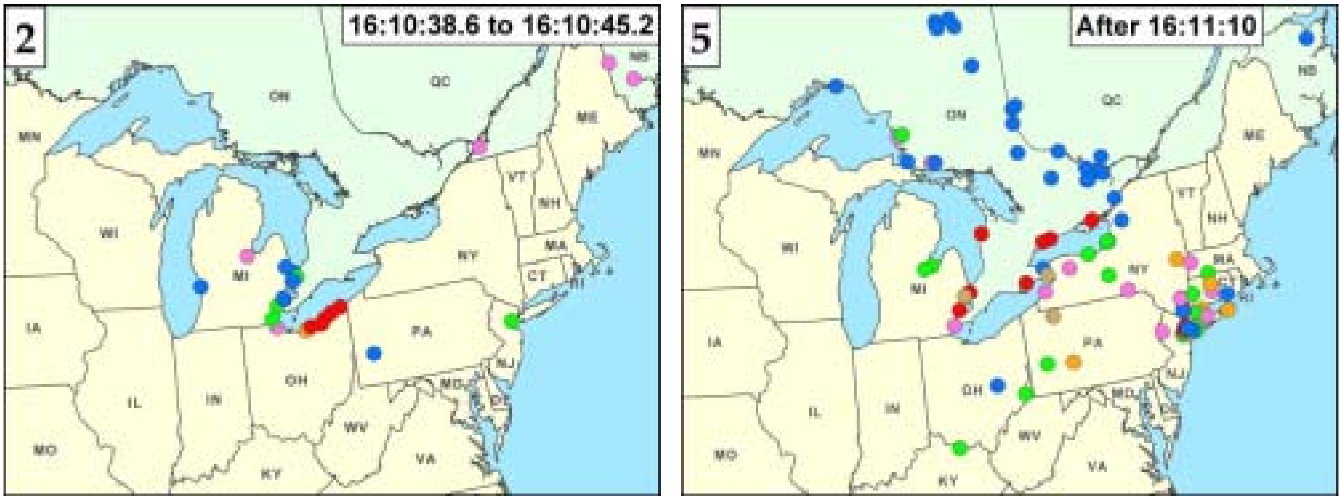
The Eastlake 5 trip at 13:31 EDT was an excitation system failure—as voltage fell at the generator bus, the generator tried to increase quickly its production of voltage on the AC winding of the machine quickly. This caused the generator’s excitation protection scheme to trip the plant off to

Figure 6.24. Generator Trips by Time and Cause



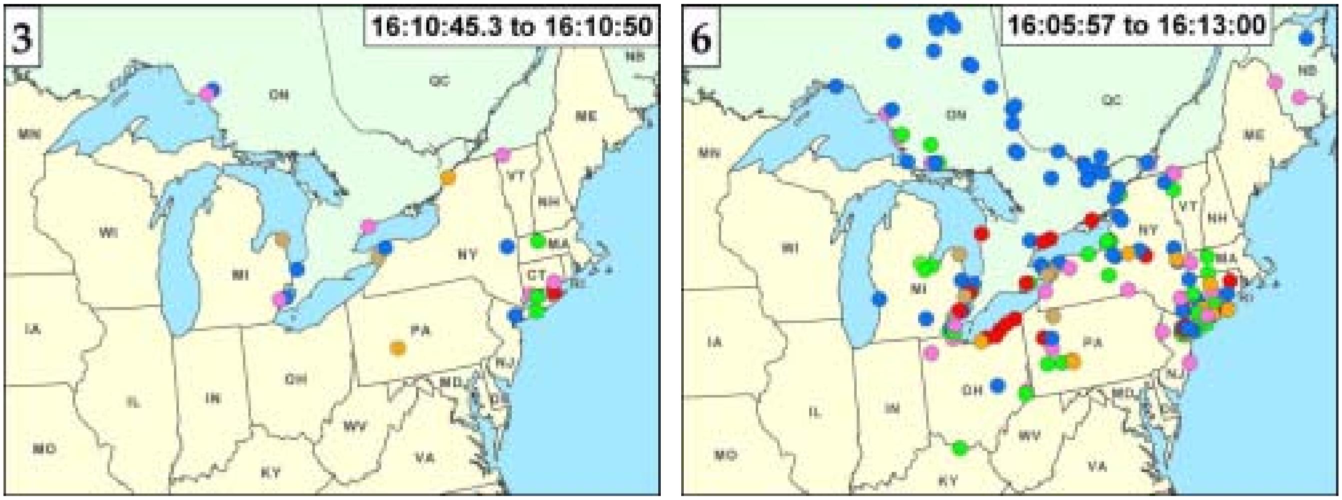
Sammis-Star to Cleveland split from PA

Ontario split from West New York to final Ontario separation



Cleveland split to Northeast separation from Eastern Interconnection

After all the separations



Northeast separation to first Ontario split from West New York

All generator trips

Map Legend: Probable Cause

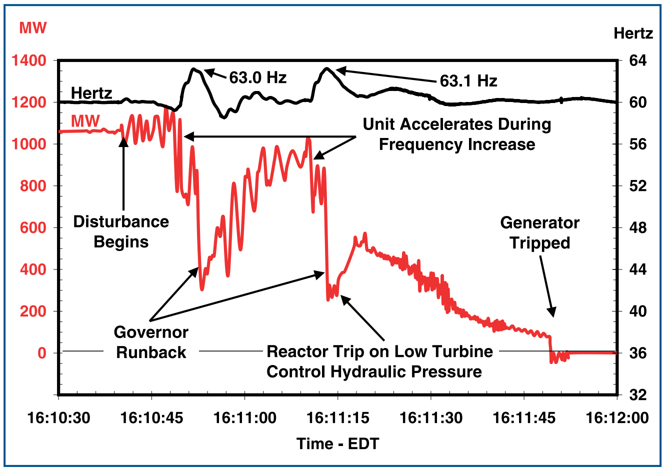
- ● Configuration Isolated
- ● Under-Frequency
- ● Under-Voltage
- ● Operator Shutdown
- ● Consequential Tripping
- ● Not Determined

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. Seventeen generators reported tripping for over-excitation. Units that trip for a cause related to frequency should be evaluated to determine how the unit frequency triggers coordinate with the region's under-frequency load-shedding scheme, to assure that the generator trips are sequenced to follow rather than precede load-shedding. After UFLS operates to drop a large block of load, frequency continues to decline for several cycles before rebounding, so it is necessary to design an adequate time delay into generators' frequency-related protections to keep it on-line long enough to help rebalance against the remaining load.

Fourteen generators reported tripping for under-excitation (also known as loss of field), which protects the generator from exciter component failures. This protection scheme can operate on stable as well as transient power swings, so should be examined to determine whether the protection settings are appropriate. Eighteen units—primarily combustion turbines—reported over-current as the reason for relay operation.

Some generators in New York failed in a way that exacerbated frequency decay. A generator that tripped due to a boiler or steam problem may have done so to prevent damage due to over-speed and limit impact to the turbine-generator shaft when the breakers are opened, and it will attempt to maintain its synchronous speed until the generator is tripped. To do this, the mechanical part of the system would shut off the steam flow. This causes the generator to consume a small amount of power off the grid to support the unit's orderly slow-down and trip due to reverse power flow. This is a standard practice to avoid turbine over-speed. Also within New York, 16 gas turbines totaling about 400 MW reported tripping for loss of fuel supply, termed "flame out." These units' trips should be better understood.

Figure 6.25. Events at One Large Generator During the Cascade



Another 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. At least 17 units reported tripping due to loss of system configuration, including the loss of a transmission or distribution line to serve the in-plant loads. Some generators were tripped by their operators.

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Unfortunately, 40% of the generators that went off-line during or after the cascade did not provide useful information on the cause of tripping in their response to the NERC investigation data request. While the responses available offer significant and valid information, the investigation team will never be able to fully analyze and explain why so many generators tripped off-line so early in the cascade, contributing to the speed and extent of the blackout. It is clear that every generator should have some minimum of protection for stator differential, loss of field, and out-of-step protection, to disconnect the unit from the grid when it is not performing correctly, and also protection for protect the generator from extreme conditions on the grid that could cause catastrophic damage to the generator. These protections should be set tight enough to protect the unit from the grid, but also wide enough to assure that the unit remains connected to the grid as long as possible. This coordination is a risk management issue that must balance the needs of the grid and customers relative to the needs of the individual assets.

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Key Phase 7 Events

Electric loads and flows do not respect political boundaries. After the blackout of 1965, as loads grew within New York City and neighboring northern New Jersey, the utilities serving the area deliberately increased the integration between the systems serving this area to increase the flow capability into New York and 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 southwest Connecticut, and moved the weak spots on the grid out past this combined load and network area.

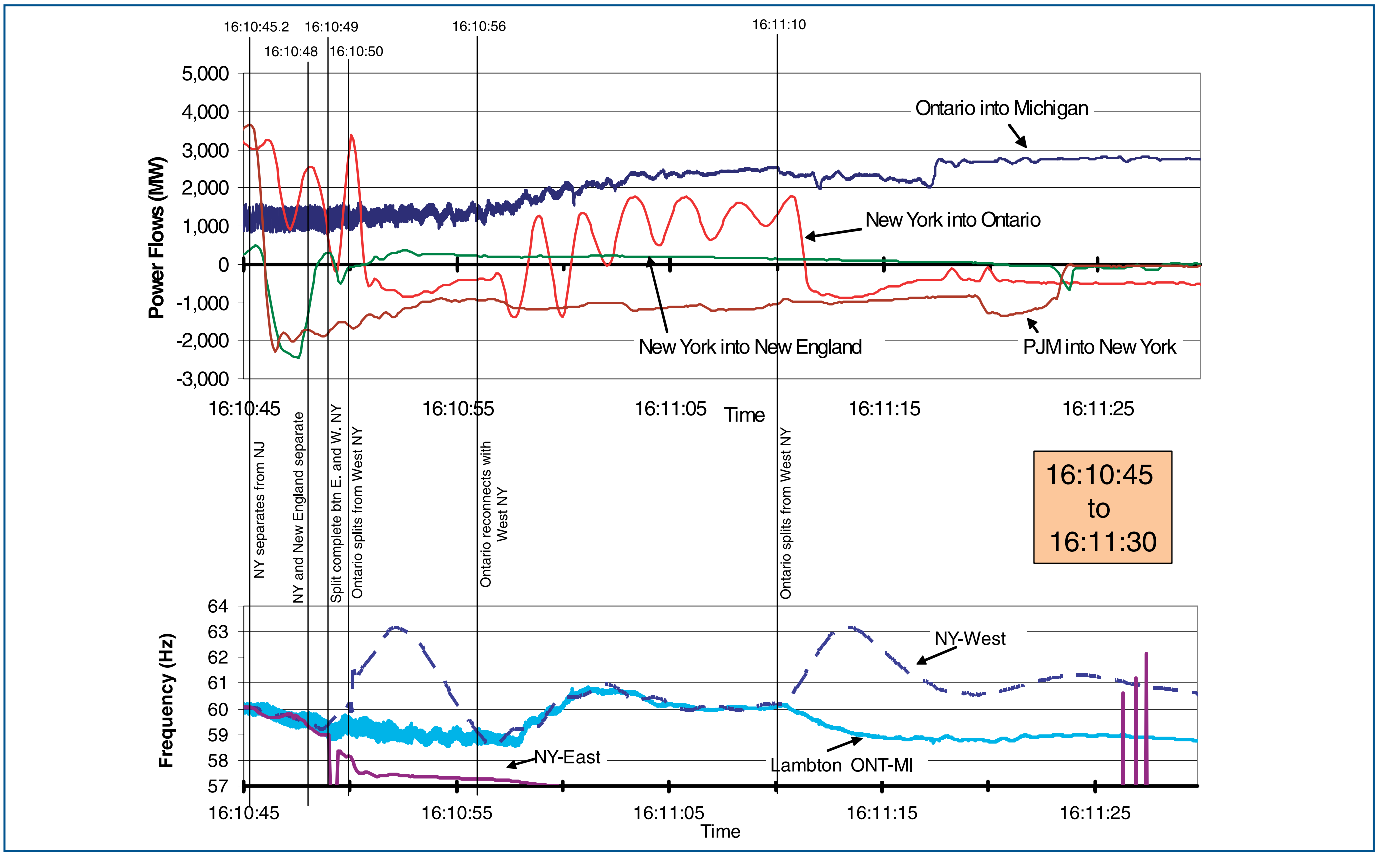
Figure 6.26 gives an overview of the power flows and frequencies in the period 16:10:45 EDT through 16:11:00 EDT, capturing most of the key events in Phase 7.

7A) New York-New England Transmission Lines Disconnected: 16:10:46 to 16:10:54 EDT

Over the period 16:10:46 EDT to 16:10:54 EDT, the separation between New England and New York occurred. It occurred along five of the northern tie lines, and seven lines within southwest Connecticut. At the time of the east-west separation in New York at 16:10:49 EDT, 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 EDT. Because New England was exporting to New York before the disturbance across the southwest Connecticut tie, but importing on the Northwalk-Northport tie, the Pleasant Valley path opened east of Long Mountain—in other words, internal to southwest Connecticut—rather than along the actual New York-New England tie.[5] 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.[6] 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 the New England area along with Canada's Maritime Provinces (New Brunswick and Nova Scotia) became an island with generation and demand balanced close enough that it was able to remain operational. The New England system had been exporting close to

Figure 6.26. Measured Power Flows and Frequency Across Regional Interfaces, 16:10:45 to 16:11:30 EDT, with Key Events in the Cascade



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 EDT, voltages became depressed across portions of New England and some large customers disconnected themselves automatically.[7] However, southwestern Connecticut separated from New England and remained tied to the New York system for about one minute.

While frequency within New England wobbled slightly and recovered quickly after 16:10:40 EDT, frequency of the New York-Ontario-Michigan-Ohio island fluctuated severely as additional lines, loads and generators tripped, reflecting the severe 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 (HVDC) 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.

7B) 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 on-line to balance load. Frequency declined quickly to below 58.0 Hz and triggered 7,115 MW of automatic UFLS.[8] 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 EDT. The western portion of New York remained connected to Ontario and eastern Michigan.

The electric system has inherent weak points that vary as a function of the characteristics of the physical lines and plants and the topology of the lines, loads and flows across the grid at any point in time. The weakest points on a system tend to be those points with the highest impedance, which routinely are long (over 50 miles or 80 km) overhead lines with high loading. When such lines have high-speed relay protections that may trip on high current and overloads in addition to true faults, they will trip out before other lines in the path of large power swings such as the 3,500 MW power surge that hit New York on August 14. New York's Total East and Central East interfaces, where the 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 before 16:10:00 EDT, the area had been importing electricity and had less generation on-line than load. At 16:10:50 EDT, seconds after the separation along the Total East interface, the eastern New York area had experienced significant load reductions due to under-frequency load-shedding—Consolidated Edison, which serves New York City and surrounding areas, dropped over 40% of its load on automatic UFLS. But at this time, the system was still experiencing dynamic conditions—as illustrated in Figure 6.26, 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. But the available information indicates that 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 southwest 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.

The team could not find any way that one electrical region might have protected itself against the August 14 blackout, either at electrical borders or internally. The team also looked at whether it was possible to design special protection schemes to separate one region from its neighborings proactively, to buffer itself from a power swing before it hit. This was found to be inadvisable for two reasons: (1) as noted above, the act of separation itself could cause oscillations and dynamic instability that could be as damaging to the system as the swing it was protecting against; and (2) there was no event or symptom on August 14 that could be used to trigger such a protection scheme in time.

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 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 EDT, frequency in Ontario declined below 59.3 Hz, initiating automatic under-frequency load-shedding (3,000 MW). This load-shedding dropped about 12% of Ontario's remaining load. Between 16:10:50 EDT and 16:10:56 EDT, the isolation of Ontario's 2,300 MW Beck and Saunders 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 63.4 Hz due to excess generation relative to the load within the island (Figure 6.27). 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 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 19% of Ontario demand (4,800 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 the loss of 22,500 MW of load in Ontario, including the cities of Toronto, Hamilton, and Ottawa.

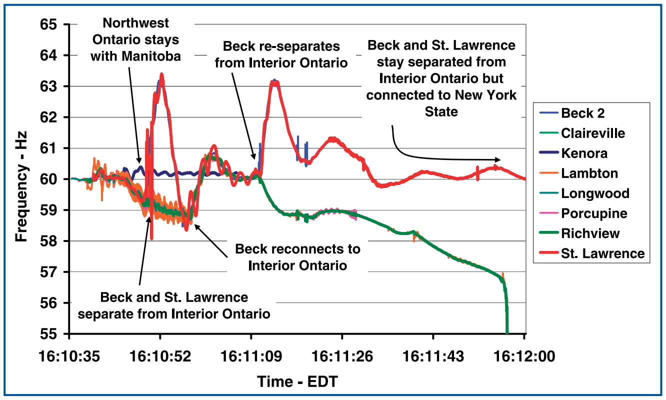
7D) Southwest Connecticut Separated from New York City: 16:11:22 EDT

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 line 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 New York, including the heavily populated areas of southeastern New York, New York City, and Long Island, experienced severe frequency and voltage declines. 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

Figure 6.27. Frequency Separation Between Ontario and Western New York



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, via 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 to the Québec HVDC tie, remained connected to the western New York system, supporting demand in upstate New York.

Electrical islanding. Once the northeast became isolated, it lost more and more generation relative to load 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 6.28. Electric Islands Reflected in Frequency Plot

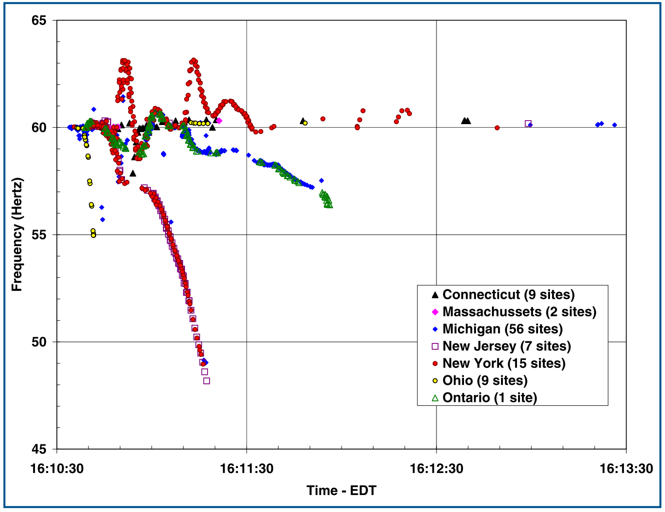


Figure 6.28 shows frequency data collected by the distribution-level monitors of Softswitching Technologies, Inc. (a commercial power quality company serving industrial customers) for the area affected by the blackout. The data reveal at least five separate electrical islands in the Northeast as the 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 6.29) 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.

One relatively large island remained in operation serving about 5,700 MW of demand, mostly in western New York, anchored by the Niagara and St. Lawrence hydro plants. This island formed the basis for restoration in both New York and Ontario.

The entire cascade sequence is depicted graphically in Figure 6.30.

Figure 6.29. Area Affected by the Blackout

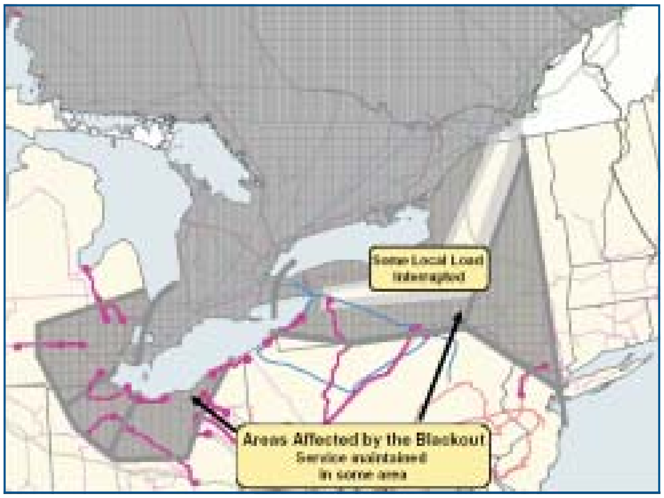
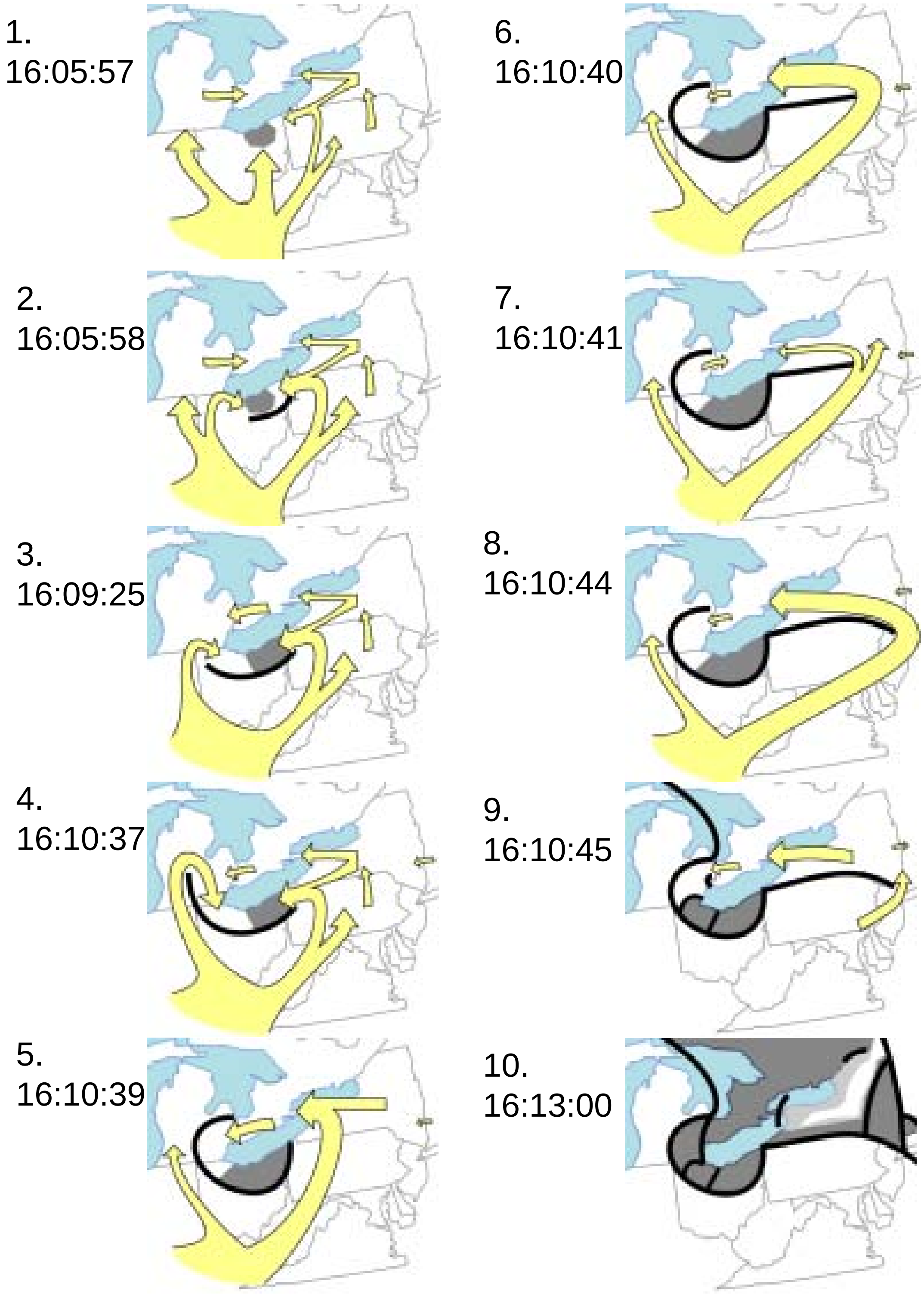


Figure 6.30. Cascade Sequence



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.

Endnotes

[1] New York Independent System Operator, *Interim Report on the August 14, 2003 Blackout*, January 8, 2004, p. 14.

[2] *Ibid*., p. 14.

[3] These zone 2s are set on the 345-kV lines into the Argenta substation. The lines are owned by Michigan Electric Transmission Company and maintained by Consumers Power. Since the blackout occurred, Consumers Power has proactively changed the relay setting from 88 Ohms to 55 Ohms to reduce the reach of the relay. Source: Charles Rogers, Consumers Power.

[4] The province of Québec, although considered a part of the Eastern Interconnection, is connected to the rest of the Eastern Interconnection only by DC ties. In this instance, the DC ties acted as buffers between portions of the Eastern Interconnection; transient disturbances propagate through them less readily. Therefore, the electricity system in Québec was not affected by the outage, except for a small portion of the province's load that is directly connected to Ontario by AC transmission lines. (Although DC ties can act as a buffer between systems, the tradeoff is that they do not allow instantaneous generation support following the unanticipated loss of a generating unit.)

[5] New York Independent System Operator, *Interim Report on the August 14, 2003 Blackout*, January 8, 2004, p. 20.

[6] *Ibid*., p. 20.

[7] 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.

[8] New York Independent System Operator, *Interim Report on the August 14, 2003 Blackout*, January 8, 2004, p. 23.