The August 14th, 2003 Blackout

ECE 554
Power Systems Relaying

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Photo of the New York City skyline during the night of the August 14th, 2003 Blackout

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I. Introduction

Every year, hundreds of thousands of disturbances occur on the United States modern power system [2]. Most of these disturbances go unnoticed due to well-engineered system protection such as relaying protection devices, reclosers, fuses, and other protection devices. System personnel such as operators and support staff continuously monitor the system every day to prevent significant events before they happen. A small fraction of disturbances result in significant system failures, and sometimes can affect a region of people who depend on reliable electricity. Consequences of these failures not only impact the national economy but the health and safety of people. The August 14th, 2003 blackout affected an estimated 50 million people and cost an estimated $4 billion to $10 billion in damage [1]. The recent blackout and its consequences made popularly known the problems in how power is planned, operated and managed.

Electricity can be named one of the greatest engineering achievements [1]. The US has an estimated $1 trillion investment in the electric system serving well over 283 million people. Dependable electricity is an essential resource for national security, communications, health, food and water supply, transportation, etc [1]. Although people expect electricity to be 100% reliable, customers expect infrequent outages due to storms and localized events. However, widespread and long outages such as blackouts are rare, but unforgivable. But can one really “prevent” all blackouts? System theorists have statistically studied the electric power system and its performance and concluded that big blackouts are a natural product of the power grid and are inevitable just as earthquakes are inevitable in leveling Tokyo [2]. A Carnegie Mellon team of researchers argued that the limitations of modeling preclude our knowledge of preventing blackouts and that people, including governments, should focus more on surviving the blackouts [2]. *Figure 1* illustrates the studies done by this research team to statistically likely.

Figure 1 – Internet photo documenting the hardship of people displaced and trapped within New York City as a result of the August 14th, 2003 blackout. Many people could not make it home and stayed in the dark city where food, water, and shelter were scare.

Since blackouts can and will happen, it is important to study and understand them to minimize the frequency, influence, and duration of these significant system failures in the future. As an analyst in the operations of transmission and energy management systems, I have benefited from studying the August 14th, 2003 blackout report. Knowing the extent of day-to-day operations, data modeling, and software functionality has had on contributing to the 2003 blackout; I have become more aware of the importance of my work.

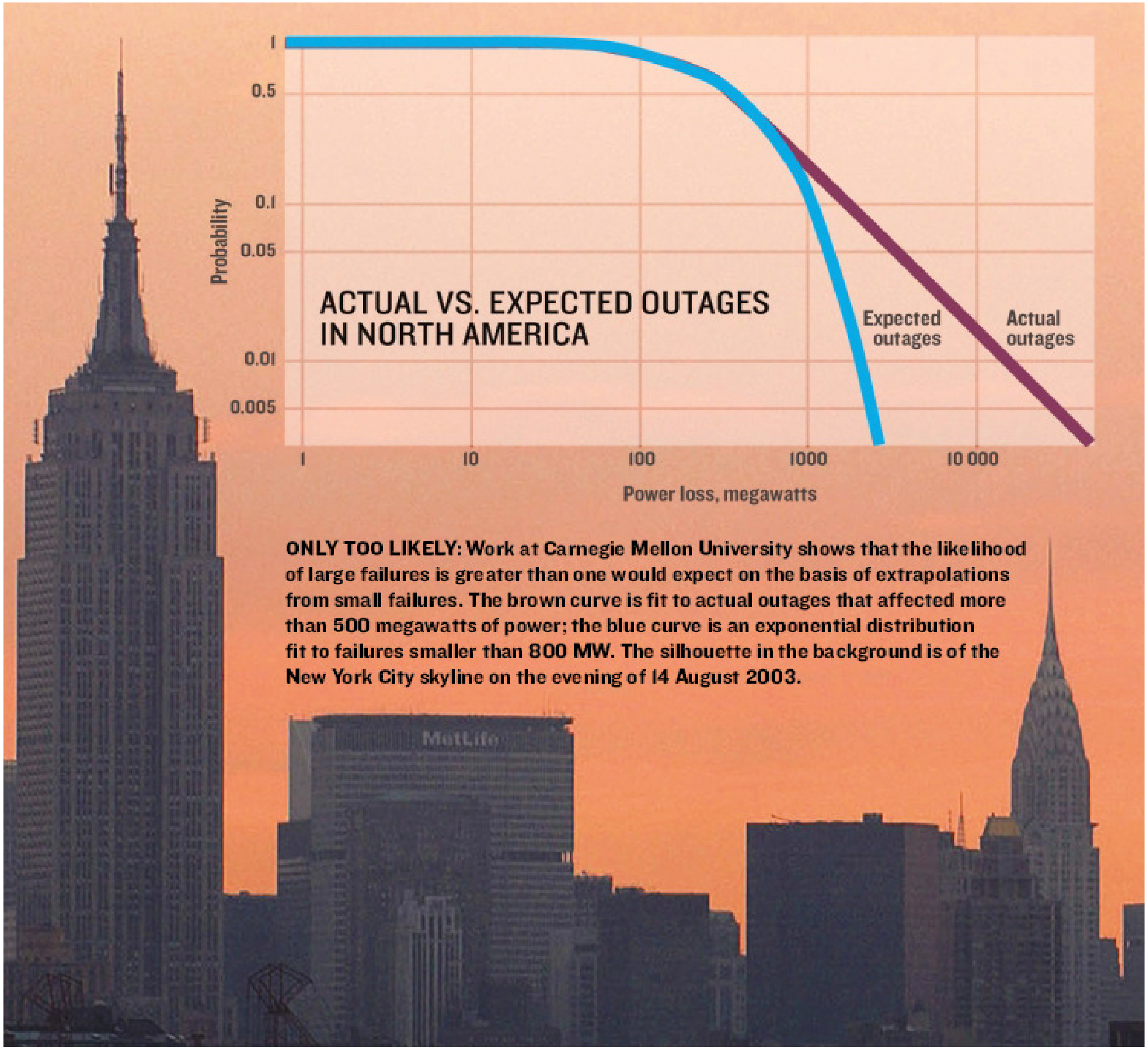

Figure 1 – Probability of Blackouts are proven statistically likely

I am pleased to provide technical documentary of the events leading to and including the outage of 50 million Americans. Relaying and system protection has played a major contribution to the cascade of an outage that could have been contained within one localized area. An overview of the August 14th, 2003 blackout will be discussed in summary. The role of relaying and system protection in contributing to the cascade of outages in other areas will then be discussed in detail. After the blackout, system restoration took coordinated planning and often days to restore all customers affected by the blackout. The restoration and protection issues after the blackout event will also be discussed. The aftermath of the blackout sparked massive government and utility investigations. Legislation passed through Congress granted organizations new roles, responsibilities, and powers to *enforce* reliability and cooperation of stakeholders and asset owners in the North American power grid.

II. Overview of August 14th, 2003

Before the Blackout

Before the August 14th, 2003 the Cleveland-Akron area was especially vulnerable to voltage insecurity and both ECAR and FirstEnergy failed to plan and implement actions to ensure the security of the power feeding the area. They did not operate the system with appropriate remedial actions (like load shedding) in regards to the decaying voltage situation right up before the blackout. [1]. NERC has found them to be in multiple violations in regards to contributing to the declining security just before the blackout and failure to notify their transmission neighbors when they experienced problems. The Cleveland-Akron area bought reserves and power from lines feeding the metropolis. Reactive power cannot travel far from the source. With little planned backup reactive power feeding the Cleveland-Akron area, the operators found themselves operating on thin reserves when the load began to inch closer to the peak load.

The operators had other difficulties just up to the blackout. Their energy management systems were unreliable and had "restarts" to try and fix the software that allows operators to control the equipment on the system. In addition, ECAR's state estimator was not functional to detect inadequacies in the current state of operations, such as failed contingencies as a result of generation facilities being unavailable (like Eastlake Unit 5 being tripped). On this day 4 out of 5 capacitor banks were out of service. These major sources of static reactive support were removed from the system that should have been available to meet peak loads. It is normal practice to outage capacitor banks for maintenance during off-peak season [1]. Only FirstEnergy knew about these reactor banks out of service. MISO had successfully ran day-ahead studies considering both generation and transmission outages.

Since reactive power does not travel far, especially under heavy load conditions, it must be generated close to its area of consumption. Control areas must carefully monitor and evaluate system conditions in heavily loaded urban load areas like the Cleveland-Akron area to ensure the reactive reserves can adequately meet the voltage schedules [1]. The Eastlake Unit 5 unit, just west of Cleveland on Lake Erie, was a major source of supplying reactive power to the urban load center. When the unit tripped before the blackout, voltage management in northern Ohio became a real challenge to FE operators [1]. The loss of this unit caused a contingency to fail. If the Perry plant, another significant provider of reactive power to this load center, failed, then the area would be shorted of reactive power to meet the local demand. Another consideration in reactive power operation and planning is the balance between static and dynamic reactive power. Before the blackout, with so little generation left in Cleveland-Akron area, the area's dynamic reserves were depleted and the area relied heavily on static compensation to support voltages. System relaying on static compensation can experience a gradual voltage degradation followed by a sudden drop in voltage stability. On August 14, the lack of adequate dynamic reactive reserves, coupled with not knowing the critical voltages and maximum import capability to serve native load, left the Cleveland-Akron area in a very vulnerable state [1]. *Figure* 2 shows a good diagram of reactive margins contributing to system stability.

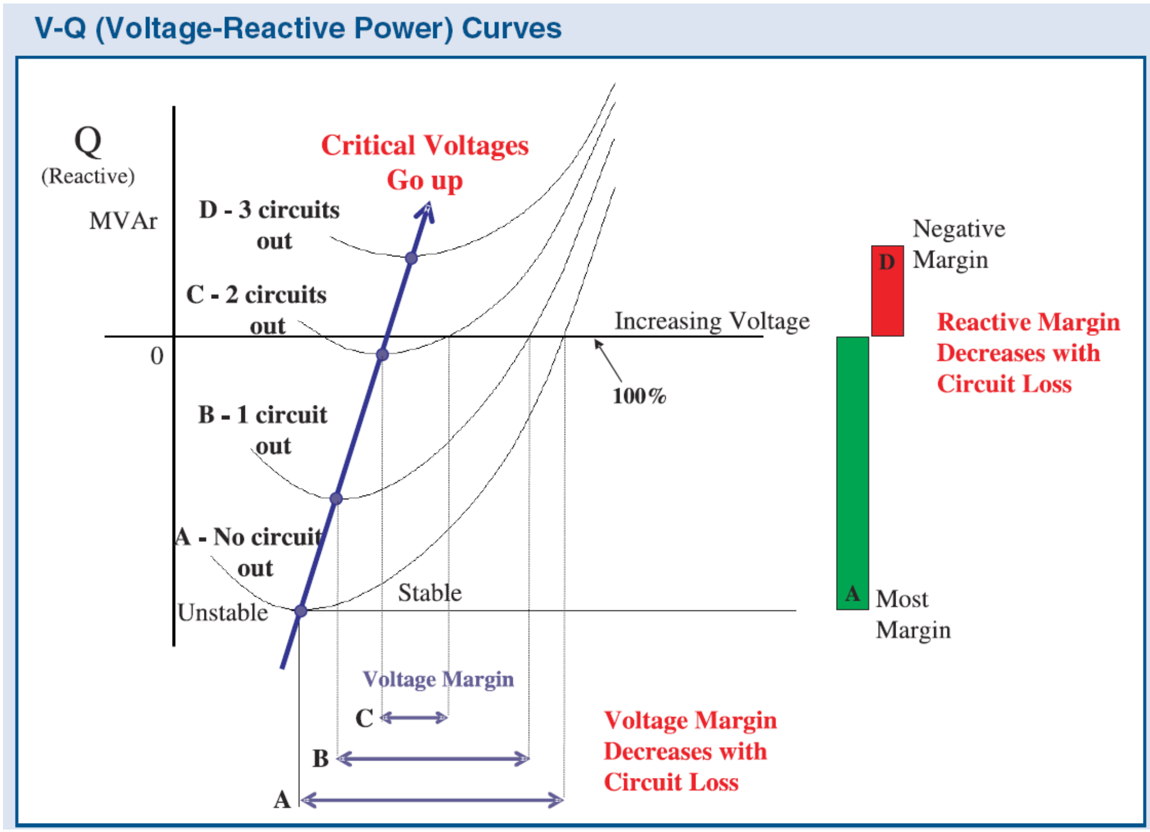

Figure 2 – V-Q (Voltage-Reactive Power) Curves and Stability

It is also significant to note, that transmission curtailments around the Cleveland-Akron area would have had minimal impact on the loading and the declining voltage situation in the area. Power flow patterns and transactions did not cause the blackout in the Cleveland-Akron area. But once the first four FirstEnergy lines went down, the magnitude and pattern of flows on the overall system did affect the ultimate path, location and speed of the cascade after 16:05:57 EDT [1].

Studies, modeling, and simulations play an important role in assessing the capabilities of the power system to perform well under emergency conditions. FirstEnergy and their reliability coordinator, ECAR, failed to conduct adequate studies of their system. Their studies were not robust, thorough, or up-to-date. FE's planners and operators were thus deficient in their understanding of their system risks under emergency situations [1]. Before the August 14th 2003 Blackout, AEP had conducted long-term studies for up to 2007 [1]. These studies were done on the area in advance to plan for and prepare for the 2003 summer. Studies showed that with heavy transfers to the north, overloading of the south canton transformer, and depressed voltages would occur following the loss of the Perry unit and the loss of the Tidd-Canton central 345-kV line, and probable cascading into voltage collapse across northeast Ohio would occur for nine different N-2 contingencies. AEP *shared* these findings with FirstEnergy in a May

2003 meeting. Neither party was able to identify changes to be done for the 2003 summer to be able to control power flows through the heavily loaded canton transformer bank.

The system was in a reliable operational state before 15:05 EDT. Unusual system conditions before this time were eliminated as sole causes of the blackout [1]. Although FirstEnergy system was technically in secure electrical condition before 15:05 EDT, it was still highly vulnerable. Analysis of Cleveland-Akron area voltages and reactive margins shows that FirstEnergy was operating that system on the very edge of NERC operational reliability standards and could have compromised system security [1]. The vulnerability created by inadequate system planning and understanding by FirstEnergy was exacerbated because the FirstEnergy operators were not adequately trained or prepared for the emergency situations.

How and Why the Blackout Began – A Brief Summary

The point of no return for system stability occurred around 15:46 EDT when FE, MISO, and neighboring utilities realized the FE system was unstable, and that the only way to prevent the blackout would have been to shed 1,500 MW of load in the Cleveland-Akron area. No effort for load shed was made [1]. After 15:46 EDT, the loss of some of FE's 345-kV lines in northern Ohio caused its network of 138-kV lines to fail, leading in turn to the loss of FE's Sammis-Star 345-kV line at 16:06 EDT. The loss of FE's Sammis-Star line triggered the uncontrollable 345 kV cascade part of the blackout sequence. The loss of the Sammis-Star line triggered the cascade because it shut down the 345-kV path into northern Ohio from eastern Ohio [1]. The loss of the heavily overloaded Sammis-Star line instantly created major and unsustainable burdens on lines in adjacent areas. The cascade spread rapidly as lines and generating units automatically tripped by protective relay action to avoid physical damage.

Afternoon Break Downs

During the afternoon, the Cleveland-Akron area lost two of its active and reactive power buttresses (Davis-Besse and Eastlake 4). The loss of the Eastlake 5 unit at 13:31 EDT further depleted voltage support for the Cleveland-Akron area [1]. The loss of Eastlake 5 was a significant factor in the outage later that afternoon. There was effort throughout the afternoon to support voltages but the FirstEnergy personnel attested the system conditions as not being unusual. Key events during the afternoon started with MISO's state estimator not fully functional working to assess the reliability of the area. This prevented real-time contingency analysis tools from performing pre-contingency or "early warning" assessments of power system reliability [1]. Eastlake Unit 5 (a primary buttress for voltage security in the Cleveland-Akron area, see *Figure 3*) tripped offline. Also the 345 kV Stuart-Atlanta transmission line tripped. The combination of these events led to the degradation of the power system and contributed to the August 14th, 2003 blackout.

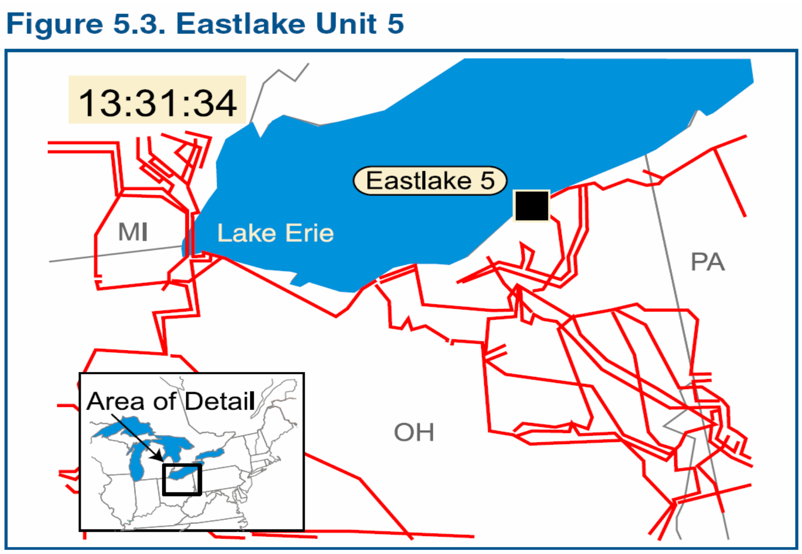

Figure 3 – Eastlake Unit 5 Map

Computer Problems

Around 14:14 EDT of the afternoon of August 14th, 2003 the FE operators lost alarm functionality that indicates equipment changes into problematic conditions [1]. The EMS (energy management systems) lost many of its remote control consoles. Also, the primary and backup server computers that hosted the alarms experienced significant delays and failures. It is interesting to note, that operators in the FirstEnergy control room did not know of the absence of alarms and computer problems for over an hour. Without working computers and energy management software, the FirstEnergy system operators were unaware that their system was failing, especially when the Star-Canton 345 –kV line tripped.

Transmission Line Failures

From 15:05:41 EDT to 15:41:35 EDT, three 345-kV transmission lines failed at or below each line's emergency rating [1]. Each failure was the result of tree contact due to inadequate vegetation management. After each line failure, loading on neighboring lines increased heavily. After each transmission line failure, the power paths flowed on other lines and voltages degraded. The loading also increased and voltage decreased on underlying 138-kV lines serving the Cleveland-Akron area [1]. These 138-kV lines quickly became overloaded. According to relay autopsies, these 138-kV lines ground-faulted, due to the overloading and sagging of the conductors low enough to contact something at ground potential. With the line tripping, the voltages dropped and caused some customers to shed themselves from the grid to protect their voltage-sensitive equipment. After the 138-kV lines opened, many customers were blacked out. The 345-kV Sammis-Star line stayed in service until it tripped at 16:05:57 EDT. It has been concluded that after this line tripped, the possibility of averting the cascade by shedding load ended. Within 6 minutes of this overload, system instability would blackout the Eastern Interconnection.

III. The Cascade

After the Sammis-Star 345-kV line tripped in Ohio, many lines began to trip. Many of the following lines that tripped operated on zone 3 impedance relays (or zone 2 relays set to operate like zone 3s), which responded to the overloaded lines rather than fault impedances [1]. The speed of the tripping of these relays accelerated and spread beyond the Cleveland-Akron area (*see Figure 4*). Relay autopsies suggest that relay protection settings for the transmission lines, generators and under-frequency load-shedding in the northeast may have not been suitable and coordinated to reduce cascades [1]. But they were not intended to do so originally.

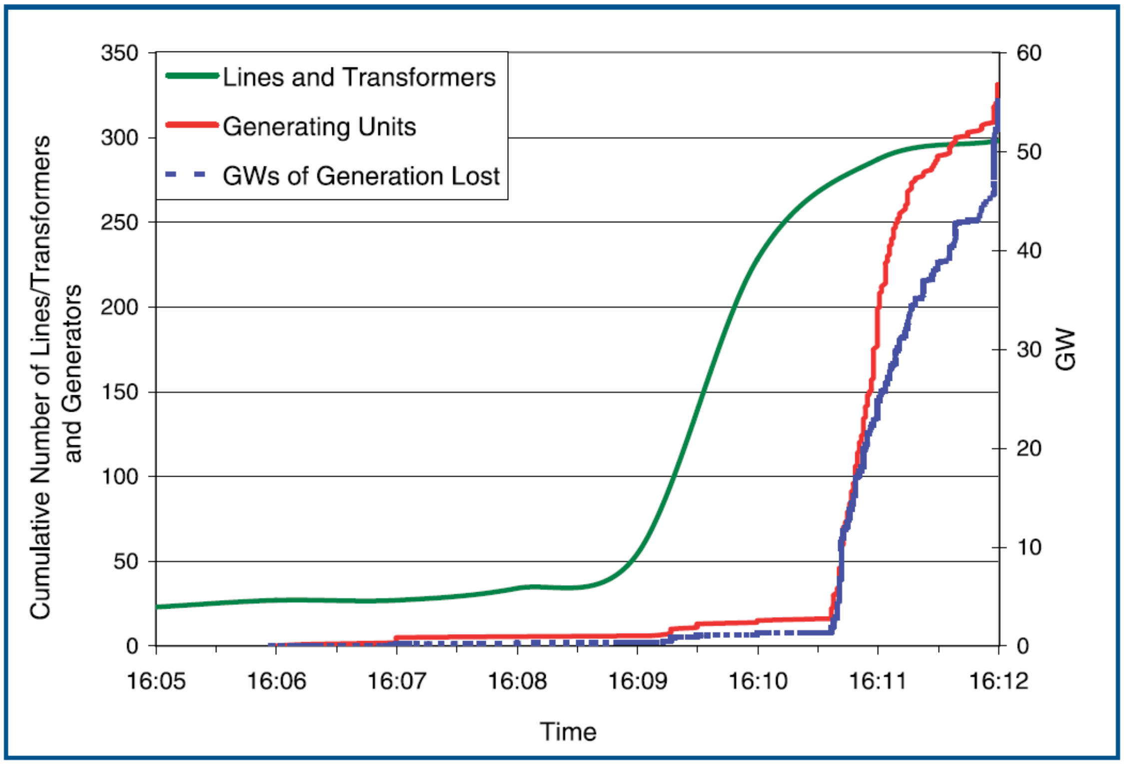

Figure 4 – Rate of Line and Generator Trips during the Cascade

The Cascade Evolution

The heavily loaded lines in the Cleveland-Akron area before the cascade lead to the trip of the key Sammis-Star 345-kV line 16:05:57 EDT [1]. It was this line trip that triggered the domino-like cascade of line and generator tripping. The electrical system became like a giant wave-tank of fluctuating electrical phenomenon that brought forth its wrath across the northeast United States and Canada. In only 7 minutes, it had left incredible devastation: tens of millions of people in both the United States and Canada were without electric power. After the cascade initiated at about 16:06 EDT, it evolved into different segments, which will be discussed.

Phase 5

The collapse started with shifts of power transfer all across the region. Before the collapse, flows were moving across FE's system from generators in the south and west to load centers in northern Ohio, eastern Michigan, and Ontario [1]. Several lines within northern Ohio began to trip under the heavy load it carried as a result of other lines tripping. Zone 3 impedance relays sped up the tripping times of these heavily loaded lines. Each line trip caused shifts in power flows and loadings. After the Sammis-Star 345-kV line tripped and the underlying 138-kV system was lost, there were no large capacity transmission routes left from the south to support the load in northern Ohio (*see Figure 5*). Since the load could not be fed from the south, it was up to the west route to try. The transmission lines from the west and northwestern Michigan became heavily loaded and tripped more lines and generator units.

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

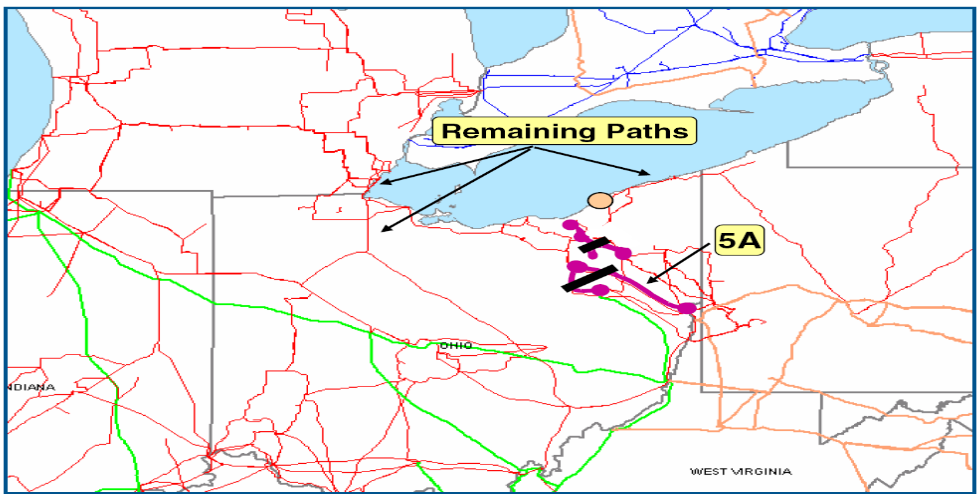

Figure 5 – Sammis-Star 345-kV line trip and affected transmission routes

Zone 3 relays in the northeastern interconnection were designed to provide backup for breaker failure and remote faults on transmission lines. The zone 3 relays were designed to allow primary protection (zone 1 and zone 2) to operate first. Some lines were set with zone 3 impedances close to the long-term emergency rating of the line. With lines being heavily overloaded in extreme contingency conditions, these relays can operate. It was determined also that some transmission operators set their zone 2 relays to be like zone 3 (and reaching well beyond the line for distant faults) [1]. This would later be a contributor to the cascade. In fact, the Sammis-Star line tripped on a zone 3 impedance relay. Although there were no faults on the line, the relay tripped under heavy loading. Many more began to trip because their zone 3 impedance relays overreached the layer of protection. These relays tripped so fast that operator intervention could not attempt to stop the spread of the cascade. The investigation team for the August 14th, 2003 blackout concluded that because either zone 2 or zone 3 relays tripped after each line tripped, these relays were the common mode of failure that accelerated the spread of the cascade.

Phase 6

After 16:10:36 EDT, power surges from the FE system failures caused neighboring areas to overload their lines. Just like impedance relays contributed to blacking out the Cleveland-Akron area, the relays on other lines operated and continued to the cascade of the blackout. The first wave of tripping separated AEP from FE. Line trips spread into eastern Michigan causing a power flow reversal within Michigan to Cleveland. Once again, zone 3 relays contributed to many of these line trips. After the Cleveland-Akron area was cut off from the west, a massive power surge affected PJM, New York, and Ontario. The relays on these lines tripped in response to the massive power surge leaving very few lines still connected in Ontario. The northeastern United States and eastern Ontario then became one large electrical island. Unfortunately, in this island there was not enough generation on-line to meet the demand. The island shrunk as some areas to the south and west split in response to this. Once the northeast split from the rest of the Eastern Interconnection, the cascade was isolated.

Phase 7

The final phase began after 16:10:46: EDT when the newly formed electrical island in the northeast has less generation than load [1]. Furthermore, it was unstable due to large power surges and swings in frequency and voltage. The large island broke up into many islands. Because of this, many lines and generating units tripped until equilibrium was established in each island. Many of the island were completed blackout out, but some islands did stabilize the load and generation and remained in service. After the cascade, most areas affected by power surges were blacked out.

Why the Cascade Stopped

Because the effects of the electrical disturbance travel over power lines and decrease the further they are from the starting point (kind of like ripples on water), the swings seen by relays on lines farther away from the first disturbance may not have been enough to cause the lines to trip [1]. It is known that higher voltage lines, like the 500-kV system in PJM, are more resilient in power swings and can serve to stop the spread of a cascade. Line trips also isolated some areas from the grid that were experiencing instability. However, many of these areas retained sufficient on-line generation to meet load whereas in other areas, generators tripped offline and blacked out the load. After the northeast island was formed, voltage and frequency decay enacted fast-acting automatic load shedding to help stabilize the system, which helped New England to stay online.

IV. Restoration and Protection Issues

During system restoration, and after a blackout, it is possible for protection elements to operate for the wrong reasons. The focus after a power system blackout is to bring the system back to its normal operating state as soon as possible. If not planned and considered, the protection system can hinder and delay the restoration of the power system [3]. Conditions that can occur during the blackstart of a power system will be discussed and solutions suggested so as to not compromise the underlying protection system. For brevity, only transmission line protection after a blackout will be discussed.

After a complete black out, heavy responsibility falls onto operating engineers to determine correct system status, communicate, deploy of personnel, follow procedures, etc. The blackout restoration plan needs to be implemented, which may include dispatching personnel to blackstart units and stations to begin preparing for blackstart [3]. System restoration can be defined either as small generation sources with insufficient reactive power capability or larger plants connected to insufficient load to run in a stable mode. The most important aspect of restoration is to control the voltage so that steady state, dynamic, and transient over voltages will not harm the equipment [3]. Another issue during the restoration is the availability of sufficient fault current to detect any fault during the restoration. Restoration may create abnormal scenarios for some relays and may lead to their operation. This operation can lead to re-tripping of the system being restored. The type of protection and technology of the relay affects the likelihood of operating during restoration [3].

The reconfiguration of the system during restoration may have low fault currents or low voltage conditions [3]. Relay operations during faults may be impaired and low voltages may also lead to operation during heavy loads. Transmission lines are protected by either impedance based distance protection schemes or current based protection schemes. In current based protection schemes, the fault currents available with the new system configuration should be above the minimum settings for the relay operation [3]. Insufficient short-circuit available for relay protection may not detect broken conductors or faulted phases. Also, heavy loads may impact the relay operations during restoration.

In distance based protection schemes, overcurrent fault detectors supervise “trip outputs” to prevent undesired tripped due to the loss of potential input to the relay [3]. Limited sensitivity and weak source conditions during system restoration can affect the dependability of the protection. Some relays allow the user to “block” the operation during the loss of a potential condition. However, unbalanced voltages during system restoration should be determined prior so that one can verify the relays are not blocked because of sensitive voltage settings (in the loss of potential). Some relays provide settings for the thresholds of detecting loss of potential. Some distance schemes may use sequence quantities for directional determination, and it is important to verify the threshold levels for operation so to clear faults under new system configurations [3]. Distance relays with mho characteristics and large impedance settings may operate during restoration due to heavy load and below normal voltage. The overreaching zone element settings should be considered when picking up load during restoration. Also, both the primary and backup relays should always be in service during restoration. Impedance relays without out-of-step blocking may trip lines due to transient power swings during restoration [3]. Consideration must also be made to blocking some automatic reclosing functions to ensure that this does not happened during the presence of faults and put the recovering system as risk of collapse.

Protective relay settings are generally optimized for the normal operation of the power system including some contingencies. However, the system configuration during the restoration phase continually changes and exhibits different characteristics such as different short circuit levels as would normally be seen under normal system configurations. As restoration continues, the balance between generation and load is continually being disturbed and if these deviations are large enough they can cause the operation of over/under frequency relays and therefore shed newly connected load [3]. To avoid unwanted operation of relays, steady state, dynamic, and transient simulations must be performed to assess the performance of these relays for the planned restoration steps. Temporary relay settings may be needed to inhibit relay operation during restoration. For example, wider frequency deviations can be tolerated during restoration than in an integrated system when the blackstart units are hydro generators and thermal machines are offline. Also, higher voltage variations are acceptable if voltage-sensitive loads are not yet online. Power flow simulations can be done to determine to what extent, frequency relays can be temporarily changed to ensure the quick but safe restoration after a blackout.

V. Conclusion

The August 14th, 2003 blackout was preventable and had several contributing factors including: failure to maintain adequate reactive power support, failure to ensure operation within secure limits, inadequate vegetation management, failure to identify emergency conditions and communicate them to neighboring utilities, and inadequate regional visibility over the bulk power system [1]. It is interesting to note that several causes of the August 2004 blackout are similar to that of earlier blackouts. Efforts to implement these earlier recommendations from black out investigations have not been effective.

The recommendations by the task force committee have placed emphasis on comprehensiveness, system monitoring, training, and reinforcement of reliability standards [1]. Firstly government bodies and key stakeholders in the North American electricity should commit to high reliability and provide market strategies whenever possible, but when there exists a conflict between reliability and business objectives, the resolution should be placed in favor of reliability. Consumers should also recognize that electricity and keeping certain level of reliability is definitely not free. Maintaining the grid requires ongoing investments and business expenses. Regulated companies must make a good business case for funding to provide reliability enforcements and often the regulators are pressured by consumers to minimize the cost objectives and thus relaxing the reliability constraints. Unregulated companies are driven not by reliability, but maximization of profit. Cost minimization business models can halt reliability projects in favor of waiting till end of life or utilizing assets longer than ever before.

Recommending improvements are worthless unless they are implemented. The Task Force has emphasized that the North American governments and industry needs to commitment themselves to implementing their recommendations. Performance monitoring, accountability of senior management, and enforcement of compliance with standards are among some of the teeth recently given to reliability organizations [1]. The importance of the bulk power system cannot be overstressed. Our national security, economy, people's lives, and our future rest upon the reliability and availability of the electric power system.

VI. References

[1] U.S.-Canada Power System Outage Task Force - Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations April 2004

[2] The Unruly Power Grid Advanced Mathematical Modeling Suggests the BIG Blackouts Are Inevitable Peter Fairley IEEE Spectrum August 2004

[3] Protection Issues During System Restoration
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