THE 2003 NORTHEAST BLACKOUT: ANALYSIS OF THE RISK AND UNCERTAINTY

Chevalier, Samuel C.
College of Engineering and Mathematical Sciences
University of Vermont, Burlington, VT

***Abstract*—In August of 2003, a series of cascading line trips and generator outages caused over 55 million customers to lose access to electrical power. Although this remains the largest power outage in US history, its occurrence was predicted by several studies completed by the DOE in the years prior [4]. This catastrophe shall be introduced and outlined, and then the entire event shall be analyzed within the context and nomenclature of engineering system reliability.**

***Index Terms*—Power System Stability, Voltage Collapse, Cascading Failure, Blackout**

I. Introduction & Overview of the 2003 Disaster

A. Correlated Outages

In order to understand the blackout which took down power infrastructure in eight US states and two Canadian provinces [1], the notion of a cascading blackout (or cascading failure) must be understood. As has been taught in CE370, engineering disasters may often be underestimated due to the fact that the different components of the failure seem initially to be orthogonal (and thus, uncorrelated). Cascading blackouts are, by their nature, highly correlated events. One of the many reasons for this fact is due to the implications of Equation (1).

$$L_T = (1 + \alpha_T(T - T_0))L_{To} \tag{1}$$

This expression is used to calculate the thermal expansion (elongation) of an increasingly loaded transmission line. Clearly, a line's final length (L_T) is linearly related to the change in temperature of the line $T - T_0$. When there is some sort of disturbance in a power system, different control mechanisms and protective devices will engage automatically. The effects of these actions can have far reaching consequences. Maxwell's Equations dictate the movement of electrons in an electromagnetic field, and as Dr. Paul Hines often states, "the electrons will do as they please." Essentially, operators cannot control how the electrons flow in a system: they can only control where they can flow and how the power generation and loads are dispatched. Therefore, when a single transmission line trips, the electrons will be rerouted automatically (according to Maxwell's Equatons).

All power systems in the US should in theory be set up to achieve "N-1 security". Such security allows any single line (or transformer or similar element) to be lost while still allowing the grid to operate with no interruptions. When the electrons reroute themselves after a line trip, though, certain lines in the system become very heavily loaded, and they begin to sag according to I^2R power dissipation and (1) thermal elongation. Sagging power lines become high risk elements, since vegetation overgrowth is such a serious problem. Therefore, the loss of one line elevates the risk of losing a second line by a certain amount, making the entire blackout scenario (in some cases) a highly correlated event. As will be shown, the 2003 Northeast blackout was heavily based in these concepts.

B. Blackout Details and Timeline

The details of the 2003 blackout will now be summarized, but a more thorough investigation of the matter can be found in [1]. In a short summary, approximately 55 million people lost power, representing 63 GW of power (or 11% of the total Eastern Interconnection load). In total, 400 transmission lines and 531 generators at 261 power plants tripped (or were disconnected due to the actions of a circuit breaker or relay).

Figure 1 shows the regions affected by the power outages: eight US states and two Canadian provinces. At 15:05 Eastern Time on August 14th, 2003, the system was operating normally in most respects. There were some reactive power shortages before noon, but in general, the system was fully operational and healthy. It should be noted, though, that the Midwest's ISO (MISO) had two awareness issues: (1) its state estimator and (2) its real time contingency analysis software were both non-operational from around noon until late in the afternoon. Ultimately, this blinded MISO to the real time failures the grid was experiencing. Similarly, FirstEnergy (FE) had a number of software failures in their Energy Management Systems (EMSs) also. Both of these issues prevented operators from having good situational awareness as events started to unfold.

At 13:31, a generator in Northern Ohio was producing a very high level of reactive power. When the output was approaching its limit, the system's Automatic Voltage Regulator (AVR) tripped from automatic to manual because of overexcitation. As the operators attempted to put it back into automatic voltage regulation mode, the unit tripped offline.

Soon after the first generator tripped, a 345-kV line in FE's system tripped at 15:05 due to tree contact. The line was only loaded to 44% of its nominal rating, so the tree contact was incidental. After this, another 345-kV line tripped due to tree contact after it experienced 88% loading at 15:32. At 15:41, a third line tripped due to tree contact after experiencing 93% loading. Operational actions should have been taken by FE and

Figure 1. This map shows the regions primarily affected by the blackout. This image is reproduced from reference [5].

MISO at this point, but since much of the monitoring software was down, this did not happen.

As lines continued to cascade, very little load was lost, meaning the total load bearing was continually shifted to other lines. The most critical line trip occurred at 16:05:57. This 345-kV line was tripped by a zone 3 impedance relay (overloaded current and depressed voltage). A large series of lines in Michigan and Ohio were subsequently then tripped by more zone 2 and zone 3 relays. Before this line tripped, postmortem analysis has shown that continued cascading could have been prevented if load shedding in northeast Ohio had been implemented by system operators. Past cascading failures have shown to be accentuated by over sensitive zone 3 relays, and before 2003, NERC had made several unenforced suggestions about how to deal with the issue.

At approximately 16:10, something remarkable happened: the power began to flow backwards through the system. Power began to flow in a counterclockwise fashion, from Pennsylvania, through New York, into Ontario, and then into Michigan and Ohio. Typically, the 3700 MW of load served by this revered power flow was not met by Ontario, but Michigan and Ohio had lost all of their other major tie lines.

Soon after this point, voltage collapse began to ensue as the transmission network became increasingly loaded down. This caused hundreds of other lines and generators to trip off line as a cascading blackout engulfed the region. After the collapse, the US-Canada Power System Outage Task Force found the following four issues to be the primary causes of the blackout: Inadequate understandings of the system, Inadequate levels of situational awareness, Inadequate levels of vegetation management (tree trimming), and Inadequate levels of support from the Reliability Coordinator.

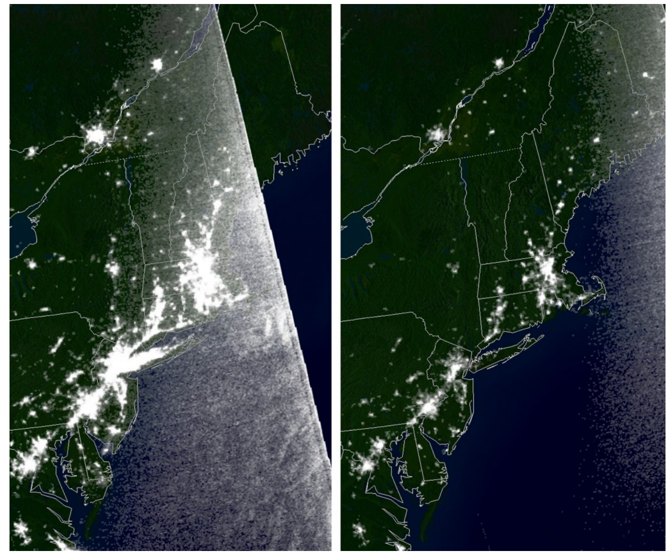

Figure 2. This image shows satellite views of part of the affected area. The image on the right was taken 27 hours after the image on the left, but both images are in the middle of the night. This figure has been reproduced from breakingenergy.com.

II. Model Class, Characteristics, and Parameters

A typical power system is modeled through a series of Differential Algebraic Equations (DAEs), as given by reference [2]. These equations model the power flows, load dynamics, and the dynamics of the voltage regulators, turbine governors, and synchronous machines. Primarily, these equations are functions of both algebraic and differential variables, but they depend on two other important system values too.

$$\begin{bmatrix} \dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f(x,y,\lambda,p) \\ g(x,y,\lambda,p) \end{bmatrix} \tag{2}$$

In 2, x represents the differential variables, y represents the algebraic variables, λ represents the system loading parameters, and p represents the control variables which the operators have authority over. In this sense, the model is derived from principles, analytical, deterministic, macro, continuous, infinite, and quantitative.

The contingency analysis and state estimators run by controllers, though, are estimated, numerical, stochastic, macro, discrete, finite, and quantitative. Ultimately, it is the load (slow base load ramping plus fast noise processes) which is the stochastic driver of the system. One very important set of parameters for this model is the network structure and strength. Particularly, operators must be aware of the series impedance ($Z = R+jX$) and shunt Admittance ($Y = G+jB$) of all lines in order to calculate the power flows on all of the transmission lines. Other important parameters include the synchronous generator winding saturation values. These indicate how much current the field windings can handle before the generator begins to malfunction and operate outside of the linear response region [3]. These values are seen as physical quantities which exist intrinsically, but in reality, they are just parameters of the model.

III. Uncertainty and Risk

A. Uncertainty

In there events leading up the blackout, operators experienced much uncertainty. In general, the largest uncertain quantity in a power system is system load. This includes load magnitude, power factor, load characteristics (constant current, constant power, etc.), high frequency noise, and more. This load is highly tied to human behavior, and it cannot be perfectly predicted, so it is therefore an aleatoric risk. In real time, though, this load level is epistemic, in that PMU devices can monitor and report the true load level (in theory) at all times. The overhanging trees represent much more of an aleatoric risk, because even though a line area might be well groomed, an animal or other unpredicted entity might change the tree's proximity to a line.

B. Risk

The risk of system failure is the product of the probability that the system fails and the economic devastation associated with the failure. In terms a cascading failure, the probability is associated with line trips (how many will occur, what is the increased probability after one line trips, etc.) , and the devastation is associated with how much of the system goes down and how long the system is down, as these two factors will determine total economic loss.

The criteria for comparison are primarily thought of in economic terms for a blackout, but there are many other considerations too. When traffic lights go down, road safety diminishes greatly, and transportation is greatly impeded. This can prevent emergency services (fire, police and rescue) from performing their duties. This puts all of society in greater danger. On extremely hot (or cold) days, customers will experience anywhere from minor to extreme discomfort as they are unable to cool or heat their homes. Civil unrest might ensue, as was the case after hurricane Sandy: citizens became very displeased with the government and with the utilities.

There are many, many hazard associated with this sort of system. As Mary Powell, the CEO of Green Mountain Power, once said, "The electricity distribution system is built to fail. When mother nature moves in, the electrical poles and towers are twigs." Of course, natural disasters are an important hazard to be aware of, but these can take many forms: flooding, hurricanes, wild fires, drought, blizzards, ice storms, and tree overgrowth. Other non-natural hazards include cyber-attacks, nuclear plant accidents, poor equipment maintenance, bad load forecasting, a lack of situational awareness, and equipment malfunctions. All of these hazards may have drastically different impacts and effects.

Sensitivity analysis, for a given system, can be performed in many ways, but one of the most important input parameters is system loading. This determines equipment stress, line sags, generator demand and ramping, reactive power needs, and so much more. Many large blackouts are associated with high system loading. Other important sensitivity elements include forecasted weather conditions, equipment age (and history), and operator monitoring and awareness capabilities. Small changes to any of these parameters can significantly alter the risk estimation.

C. Risk Estimation

At this point, five different events will be defined and their associated risks shall be estimated. The risk estimation shall be given in relation to the complete failure case, which had a true cost of $6 billion and 11 deaths. The area and timeframe are isolated to the area affect by the 2003 Blackout over the time frame which it occurred.

1) Complete Failure: Based on the definitions of the area and the timeframe, the system experienced complete system failure. 55 million customers lost access to electrical power for an extended period of time, and in many ways, they system could not have failed more dramatically: it reached its maximum state of failure. Of course, the blackout could have occurred for a longer period of time, but such an occurrence is outside our definition of the system. The risk associated with such a failure is extremely low. Estimated Risk: ($6 billion and 11 deaths) x ($\frac{1}{100{,}000}$)

2) Maximum Tolerable Failure/Minimum Acceptable Success: At 16:05, if grid operators had shed a small amount of load in northeast Ohio (~3.7 GW), the full scale blackout (63 GW) could have been avoided. Such an event would have fallen under the category of Maximum Tolerable Failure/Minimum Acceptable Success. This action would have prevented further uncontrolled line trips, and it would have shut down a very small portion of the overall load. The load shed would have been a "controlled" decision, meaning even though it would have been undesirable, it would have still been controlled by the operators. The super majority of customers in the region would have remained connected to the grid, and complete failure would have been avoided. Risk: Estimated Risk: ($500 million and 2 deaths) x ($\frac{1}{10{,}000}$)

3) Maximum Expected Failure/Minimum Expected Success: At the onset of the blackout, a generator which was producing a high level of reactive power was kicked offline. This was primarily due to over saturation of the windings, and it is not an overly uncommon event. The system should have been able to handle such a loss, but unfortunately, it was coupled with the faulting of a transmission line with an overgrown tree. If both of these events had occurred individually, the system would have remained intact. For example, the system should have the capability to lose one generator and still operate without load shedding. The unexpected loss of a generator is an example of maximum expected failure, and it should be planned for. Risk: Estimated Risk: ($5 million and 0 deaths) x ($\frac{1}{10000}$)

4) Minimum Expected Failure/Maximum Expected Success: Likely, this sort of event is how most grid operators would characterize the current day-to-day events of the grid. This grid serves its customers' needs well, but it is highly fearful of and prone to extreme weather. Customers see power outages every few months, and linemen are kept very busy fixing equipment. The future of the grid is highly uncertain as renewable energy bursts onto the scene: unfortunately, the two are incompatible. A solution will be found, but currently, the grid is appearing more and more like a necessary evil rather than a fundamental good. Risk Estimation: (Normal Operating Cost and 0 deaths) x ($\frac{99.8}{100}$)

5) Complete Success: Complete success has no upper bound, and therefore, it is extremely rare. From the perspective of a grid operator, complete success will almost never occur. In the complete success case, lines never trip and equipment never malfunctions. Customers see low rates and experience high quality, reliable power at all times. Renewable power can be integrated at very high levels, net metering policies never cap out, and Mother nature does not cause frequent power outages. The electrical grid continues to enhance human experience and become a more innovative force for good. In fact, it becomes impossible for humans to predict how the electrical grid will continue to influence societal development for the better (just as with the cell phone or personal computer). Risk Estimation: (\$0) x ($\frac{1}{?}$)

IV. Colclusion

In this paper, the causes, risks, uncertainties, and classifications for the 2003 blackout have been presented and analyzed. Overall, the blackout represented the catastrophic and complete failure of several interconnected power systems.

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Samuel C. Chevalier received a B.S. in Electrical Engineering from the University of Vermont in 2015. He is currently pursuing an M.S. degree in Electrical Engineering from UVM, and his research interests include stochastic power system stability, large scale renewable energy penetration and Smart Grid.