How a Smarter Grid Could Have Prevented the 2003 U.S. Cascading Blackout

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***Abstract*—The electrical grid is caught in a political and technological energy war over what can most efficiently, safely, reliably and cost effectively provide commercial power for an increasing national load. The answer lies in research of the 2003 Northeast Blackout and introducing an emerging technology; Smart Grid (SG). This paper summarizes the blackout's key events, driving factors and tipping point for its cascade in order to highlight the critical benefits of Smart Grid Technology (SGT). Industry research suggests that SG could have prevented the cascade, had it been complete and implemented in 2003. This paper presents the essential elements of SGT (with industry research ongoing) that can achieve three things; (1) prevent cascading blackouts of this magnitude, (2) recover as quickly as possible from emergencies (terrorist attacks, natural disasters, etc.), and (3) provide a solution to this energy war with a portfolio of energy technologies.**

Keywords—smart grid; microgrid; smart meter; northeast blackout; cascade

I. INTRODUCTION

No major event in history has been immune to intense research (post incident), resulting in change to better the applicable industry, faculty, or process. The accident that occurred at the Three Mile Island Unit 2 Nuclear Power Plant in March of 1979 was the most severe nuclear accident in a U.S. commercially operated power plant. The severity consisted of the worst case accident a nuclear plant can face (core meltdown), though it led to no injuries or casualties. This incident became a successful industry changer for the U.S. because the lessons learned resulted in drastic improvement to emergency response planning, human factors engineering, reactor operator training, radiation protection, numerous other areas of nuclear power plant operation, and caused the United States (U.S.) Nuclear Regulatory Commission (NRC) to tighten and heighten its regulatory oversight. This resulted in the positive effect of enhancing safety [1]. Research into the 2003 Northeast U.S. Blackout presents similar results when coupled with the emergent Smart Grid Technology (SGT).

The cascading blackout in 2003 was one of the largest power blackouts in North America [2] making it ripe for research and lessons learned. As complicated as the electrical infrastructure is with its many regulating authorities (deregulation) and boundaries of operation, so too are the facts that unfolded from the U.S. – Canada Task Force Final Report that attributed many causes to the blackout. The major causes will be identified per the Task Force's findings. Then, SGT will be introduced and a correlation presented between the Task Force findings and potential Smart Grid (SG) solutions. Reliability and visibility of the grid were the greatest catalysts of the 2003 cascading blackout; therefore, this paper will focus on those aspects of SGT. Amongst closing remarks, some SGT concerns and potential risks will be identified, since the technology is evolving and not fully implemented presently.

II. 2003 NORTHEAST BLACKOUT

On August 14, 2003 an estimated 50 million people and 61,800 megawatts (MW) of electric load between Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey, and Ontario, Canada were impacted by what is now commonly referred to as the 2003 Northeast Blackout [2]. The blackout began a few minutes after 4:00 pm Eastern Daylight Time (EDT), and it was determined that rolling blackouts still occurred in some locations for somewhere between four days and one week before full power was restored [2].

A. Reliability Organizations

The U.S. is divided into three electrical grids (or "the grid") shown in Fig. 1 [2]. The grid is electrically independent meaning one interconnection cannot impact another. Each interconnection is overseen by a regional reliability council that is run by the North American Electric Reliability Council (NERC) [2]. NERC is an electric reliability organization (ERO) that is certified by the Federal Energy Regulatory Commission (FERC) to establish and enforce reliability standards for the bulk-power system or grid [3]. FERC is the enveloping federal agency that regulates interstate trade in electrical energy, encompassing the wholesale electricity market [4].

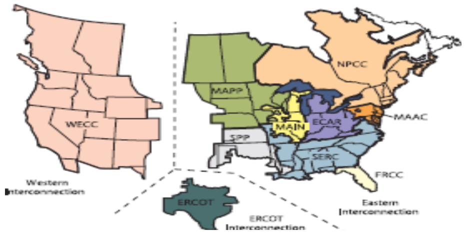

Fig. 1. U.S. grid interconnections [2].

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Reliable power operation is critical and complicated. NERC and its regional reliability councils define system operating and planning standards for ensuring transmission grid reliability. Critical reliability concepts include [2]:

- Balancing generation (supply) and load (demand) continuously,
- Balancing reactive power supply and demand to ensure voltage levels are maintained
- Monitoring power flow through transmission lines to ensure thermal heat limits are not exceeded,
- Maintaining system stability (The Task Force defines stability as the ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances [2]),
- Maintaining operation at a reliable level even if a generator was lost or another contingency were to occur (similar to the application of single failure criteria in the nuclear industry), and
- Planning in advance for emergencies [2].

Independent System Operators (ISOs) or Regional Transmission Organizations (RTOs) are single entities that balance generation and load in real time within control areas (subject to NERC), however they do not own the transmission lines they run [2]. Five ISOs/RTOs were affected by the blackout but two are mentionable: Midwest ISO (MISO) and PJM Interconnection (PJM). The key Ohio control areas involved in the blackout were First Energy (FE) – within MISO and American Electric Power (AEP) – within PJM. To summarize, NERC sets standards for safe and reliable system operation, while ISOs/RTOs are responsible for controlling operation of wholesale electricity markets within specified areas that they either control themselves or delegate to control area operators (i.e. FE, which oversees a subset of multiple utilities).

B. Causes that Started the Blackout

The conclusion presented in the Task Force's Final Report was that there was no single cause to the blackout and cascade. There was approximately four hours of numerous grid events, computer events, and human events that added to an increasing degradation of the electrical system, and that ultimately lead to the blackout and cascade [2]. The Task Force defined "'cause' not just to what happened and why it happened, but more specifically to entities whose duties and responsibilities were to anticipate and prepare to deal with the things that could go wrong" [2]. The fact that NERC lacked the authority to enforce compliance with their standards was identified as a critical flaw [2]. Multiple ISO regions within Ohio were the initializing contributors to the blackout due to deficiencies in corporate policies, lack of adherence to industry policies, and inadequate management of reactive power and voltage, rather than the lack of reactive power [2]. Four identified causes for the blackout were Inadequate System Understanding, Inadequate Reliability Coordinator Diagnostic Support, Inadequate Situational Awareness, and Inadequate Tree Trimming [2].

1) Inadequate System Understanding

Voltage and reactive power balancing is a critical reliability concern for the grid. Reactive power is not real power delivered to consumers; it is a measure of power flow in and out of electromagnetic machinery. When reactive power is consumed (heavy loads), transmission voltage decreases. Under light loads, transmission lines produce reactive power making voltage increase. Reactive power cannot be transmitted long distances; therefore it cannot be supplied quickly, so voltage can drop enough to cause collapse [2]. In transient conditions, undesirable oscillations of the system frequency and voltage magnitude can occur [5]). There were many elements that added to inadequate system understanding, but to summarize, rising load, increasingly limited generation, and reactive power imbalance were poorly managed before the blackout. To make matters worse, lack of clear and pertinent communication crippled the control area operated by First Energy (FE) [2].

2) Inadequate Reliability Coordinator Diagnostic Support

At 2:40 pm EDT it was discovered that MISO's state estimator was not running automatically on its regular 5-minute schedule [2]. An automatic trigger was re-enabled but still the state estimator failed to solve successfully. When a state estimator fails to solve successfully operators have a false sense of contingency data and system stability. Control room personnel identified the Stuart-Atlanta 345kV line outage (which occurred at 2:02 pm EDT) to be the likely cause [2]. This line is within the Dayton Power and Light (DPL) control area in southern Ohio and is under PJM's reliability umbrella rather than MISO's. Even though it affects electrical flows within MISO, its status had not been automatically linked to MISO's state estimator. The discrepancy between actual measured system flows (with Stuart-Atlanta off-line) and the MISO model (which assumed Stuart-Atlanta on-line) prevented the state estimator from solving correctly. MISO's state estimator and contingency analysis were not back under full automatic operation and solving effectively until 4:04 pm EDT, about two minutes before the start of the cascade [2].

3) Inadequate Situational Awareness

Communication breakdowns between interfacing organizations added blind spots for system operators in 2003. A few hours after MISO began having computer problems, FE's control room operator's lost alarm functionality that provided visual and audible indications (human factors engineering) when a significant event such as a piece of equipment failing or changing from acceptable to critical condition occurred [2]. FE had issues with its Energy Management System (EMS) from around 2:14 pm to 3:46 pm EDT which meant that the degrading grid events taking place at the same time were not identifiable to operators. During this time FE began to receive many phone calls from their own field personnel, MISO, PJM (concerning an adjoining system), as well as customers, however they didn't see what they were hearing about [2].

4) Inadequate Tree Trimming

Trees are an annoyance of transmission and distribution lines because they can cause short circuits to ground. Physical contact isn't always necessary for a short circuit to occur because an electric arc can occur between a part of a tree and a nearby high-voltage conductor if an adequate distance separating them isn't maintained [2]. The solution is simple; keep trees trimmed to remain outside a specified zone from power lines. It was the Stuart-Atlanta 345kV transmission line trip that contributed to MISO's state estimator failing, and it was overgrown tree lines that caused this trip in the first place [2]. The Task Force pointed out an interesting observation in their Final Report; that tree growth is slow, taking years for branches to encroach on clearance zones of power lines. Evidently, there was inadequate observation of vegetation within the control area [2].

C. Blackout to Cascade

It is now clearly evident how this perpetual cycle of faulting, increased current, overloading of lines still in service, and confusion between correspondence and indications from the operator's perspective continued to decrease reactive power and further impact voltage stability on the system. The Task Force determined that the trip of FE's Sammis-Star 345kV line at 4:05 pm EDT was the tipping point from small blackouts here-and-there in Ohio to cascading blackouts across the northeast United States and Ontario [2]. Prior to this point in time, it was believed that a cascade of line trips could have been averted [2]. A cascade occurs when there is a sequential tripping of numerous transmission lines and generators in a widening geographic area. The Task Force concluded in their Final Report that the cascade spread beyond Ohio and caused a widespread blackout for the following principal reasons [2]:

- The Sammis-Star 345kV line trip in Ohio (as well as the loss of other transmission lines previously) left the system with weak voltages and triggered many subsequent line trips.
- Many of the key lines which tripped between 4:05 pm and 4:10 pm EDT operated on relays which responded to overloads rather than true faults on the grid, and the speed at which the trips spread accelerated the cascade beyond the Cleveland- Akron area.
- Evidence indicated that the relay protection settings for the transmission lines, generators and under-frequency load-shedding in the northeast may not have been entirely appropriate and weren't integrated to reduce the likelihood of a cascade, however, they weren't intended to do so [2].

The Task Force reported that before the cascade, 16 transmission lines failed within 26 minutes and data from field relays indicated that each of these lines ground faulted [2]. It was determined that line sagging due to conductor heating and overgrown vegetation (not wind) were the common causes of tree branch impact to multiple lines [2]. Power swings and voltage fluctuations caused by these 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 [2].

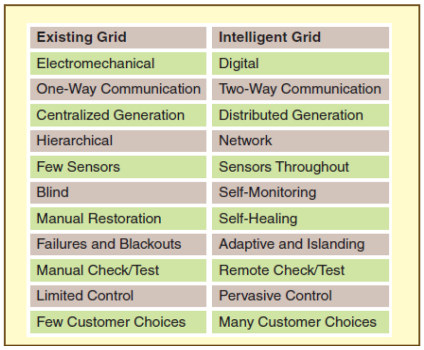
Equipment in a system must operate at the same frequency with very minimal and tightly specified variations. Generators are tripped off during a cascade to protect them from severe power and voltage swings. When generation and load aren't matched there is a frequency imbalance that occurs in the system. When generation is greater than load, frequency increases, and when generation is less than load, frequency decreases. If the change in frequency is enough then large power swings take place in the system because generators are designed to protect themselves by shutting off [2]. It was this large power flow that propelled the cascade.

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 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 [2]. This lead to increasingly more lines and generators being tripped, widening the blackout area. Power flow was forced in other directions as the system tried to stabilize remaining generation with load (to match frequency again) [2]. System frequency variation was not a cause or precursor of initiating the blackout, but as generators and other equipment were going offline in 2003, frequency variations were getting out of control, which caused more equipment to turn off and thus propagate the blackout [2].

III. SMART GRID

The present grid is only engineered to withstand maximum anticipated peak demand across its aggregated load but since this peak demand is an infrequent occurrence, the system is inherently inefficient [6]. Demand continues to increase, but the infrastructure and the technology that supports it isn't changing (until now), which is cause for stability issues. The next-generation electricity grid, known as the "smart grid" is expected to address the major shortcomings of the existing (dumb) grid [6]. Smart Grid is not one concept or one design, but is an umbrella idea for multiple technologies. SGT seeks to layer information technology, communication systems, and power system engineering to improve power flow efficiency [6]. The idea of layering information and communication technologies with power system infrastructure is a way to utilize current technologies to improve power flow efficiency.

SGT is a smart infrastructure system that gets away from the present vertical electric system (generation to load) by incorporating a network approach which supports two-way flow of electricity and information [8]. This means that electricity can be sent and received. With SGT, users could generate electricity with a wind-mill in their back yard or solar panels on their roof and send it to the grid to help balance loads by "peak shaving" (sending power to the grid when demand is high) [8]. Fig. 2 shows some key features of the smart grid in comparison with the present grid. Although the Task Force primarily focused on transmission issues in the 2003 Blackout, the roots of power system issues are typically found in the distribution system, so it is believed that investing in distribution automation will provide utilities with increasing capabilities over time [6]. Therefore, communication and data management play an important role in enabling utilities to place a layer of intelligence over their present and future infrastructure [6].



Existing Grid	Intelligent Grid
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

Fig. 2. Grid updates [6].

There is some element of command and control functions in the present grid; for instance SCADA (System Control and Data Acquisition) systems which acquire power system data from remote terminal units (RTUs) installed in the field. One issue with SCADA is that it is primarily used on transmission networks as opposed to distribution [6] which means that even if SCADA is fully operational (unlike state estimator issues in 2003) one couldn't see the whole system. Another issue with SCADA is that its technology is approximately 40 years old [7]. It does enable some elements of coordination for transmission among utilities, but it is extremely slow and much of it is still based on telephone calls between operators at control centers, especially during emergencies (like in 2003 between AEP, PJM, and FE). Furthermore, "most programmable logic controllers and remote terminal units were developed before industry-wide standards for interoperability were established; hence, neighboring utilities often use incompatible control protocols" [7].

Smart Grid aims to manage a modern grid in real time by utilizing automatic monitoring with greater interaction among operators, computer systems, communication networks and data-gathering sensors deployed in power plants and substations [8]. The SG advanced metering infrastructure (AMI) utilizes two-way communication with meters to offer utilities instantaneous information about individual and aggregated demand, as well as impose limited caps on consumption and enact various revenue models to control their costs [7]. With this technology, it would allow consumers to interact with an energy management system, allowing a sort of collaboration for adjusting energy usage and therefore cost [6]. Fig. 3 shows an example of smart metering in which a smart meter receives power consumption information from an appliance (dishwasher, TV, refrigerator, etc) and sends control commands to them if necessary. An aggregator collects meter information from different locations and routes it to a utility or distribution substation [8].

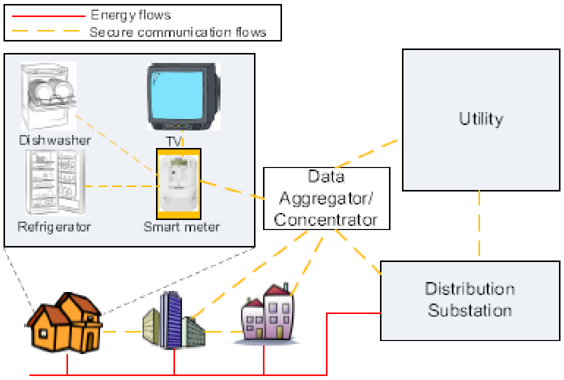


Fig. 3. Smart metering structure [8].

The Smart Grid is also unique in that it intentionally creates a microgrid topology that supports distributed generation (which is cogeneration and small power production by consumers [9]) shown in Fig. 4, where the "L" boxes are different loads. Microgrids are defined as a localized grouping of electricity generators, energy storages, and loads [8] that can function whether they are connected to or separate from the larger electricity grid [6]. The key feature is that microgrids can function autonomously through their own distributed generation [8]. The idea that electricity can flow in two directions is important because it is essential for a microgrid to be 'islanded' due to power failures, in which case the microgrid can function, albeit at a reduced level, with the help of the energy fed back by customers [8]. Had the Northeast had microgrids, large portions of the grid could have been saved by shedding load on the network since microgrids (when islands) don't obtain power from the electric utility located in the overall grid but rather from distributed generators in their microgrid [8]. With a microgrid topology that would happen automatically when the microgrid disconnected from the network and the cascade could have been completely avoided. Reliability is increased because network issues can be isolated when microgrids disconnect to island off. If the network was overloading then it is a positive move for the network too since islanding off sheds overall network load.

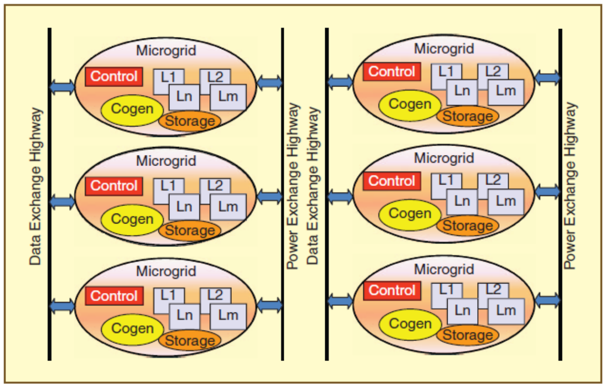


Fig. 4. Potential network of microgrids [6].

The self-healing feature of Smart Grid has three main objectives. The most essential is real-time monitoring and reaction. An array of sensors monitors electrical parameters (voltage, current, the condition of critical components, etc.). These measurements enable the system to constantly tune itself to an optimal state. The second objective is anticipation. The system will look for potential problems that could trigger larger disturbances (like a transformer overheating). Computers then assess trouble signs and possible consequences and identify corrective actions, simulate the effectiveness of each action, and present the most useful responses to human operators, who could then quickly implement corrective action by dispatching the grid's many automated control features. The industry calls this capability fast look-ahead simulation [7]. The third objective is isolation which is done by autonomous microgrids which can work well during normal operation and also continue working during outages. By appropriately controlling the system reconfiguration, the impact of disturbances or failures can be restricted within the islands or can be isolated.

Protective services in SGT aim to protect against inadvertent compromises of the grid infrastructure due to human errors, equipment failures, and natural disasters, but also from deliberate cyber attacks. The reliability and stability of SGT depends in part on the accuracy of the measurement monitoring system used [8]. A newer technology, the wide-area measurement system (WAMS) based on phasor measurement units (PMUs) is an important component for monitoring, control, and protection functions [8]. Prediction of problems as well as diagnosis of problems after they occur is part of Smart Grid protective services. An approach was developed that allows for the prediction of system weak points while determining regions of stability. From this, an automated process was created that can continuously monitor voltage constraints, thermal limits, and steady-state stability simultaneously [8]. This processing technique can improve the reliability of the transmission grid and prevent major blackouts. PMUs provide information on phase angles (think frequency compatibility) such when combined with system topology information, automated processes could determine where a line fault has occurred. Failures could occur on smart meters which would mean that load data could contain corrupted or missing information [8]. However, technology exists that Smart Grid will incorporate, that can automatically cleanse corrupted and missing data to account for this [8].

Cyber security is regarded as one of the biggest challenges in Smart Grid because it seemingly opens up the electrical grid to more vulnerabilities than it protects from [8]. One area of concern is the smart meters since they are controlled by a few central devices. Should a controller fail (intentionally or accidentally), a large portion of communication and control on the grid, which is now two-ways, would be lost. To prevent a hacker from forging a smart meter reading and guarantee the reading accuracy, a method was proposed to secure power suppliers to "echo the energy readings they receive from smart meters back to the customer" so that users can verify the integrity of the smart meter [8]. Other technology exists, such as encryption, to protect user privacy since the smart meters offer a huge opening for lack of privacy to the consumer despite their benefits [8].

Research has shown that the intent of Smart Grid is to add capabilities in an evolution of upgrades to compliment the current system [6]. It is this author's opinion that the communication layer of Smart Grid will be last, as it is the most complicated. There are many codes, standards, and protocols involved with communication networks. Fig. 5 shows one idea for a Smart Grid communication network. In this depiction, user devices and smart meters use a specification for high-level communication protocols (ZigBee), Wi-Fi, and power line communications; wireless mesh networks are used for information exchanges between users; communities are connected to their electric utility via free-space optical, satellite, microwave, or cellular systems, and a substation communicates with an electric utility over the power line 8. As Fig. 6 shows, the interface between WAN and LAN worlds consists of substation gateways, while the interface between LAN and HAN is provided by smart meters. The security and vulnerability of communication interfaces will be the focus of much technological and standardization development in the near future [6].

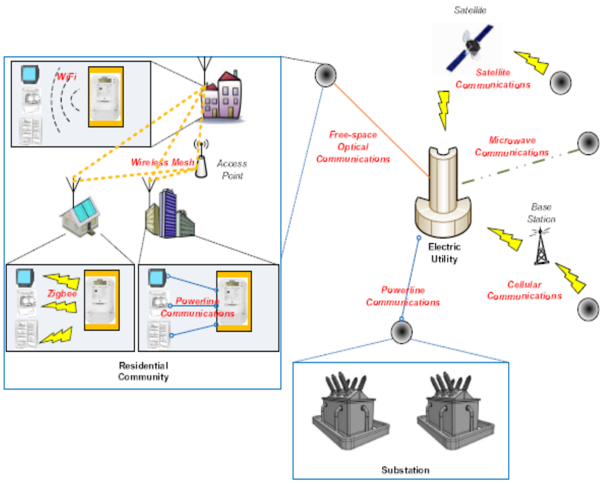


Fig. 5. Potential SG communication network [8].

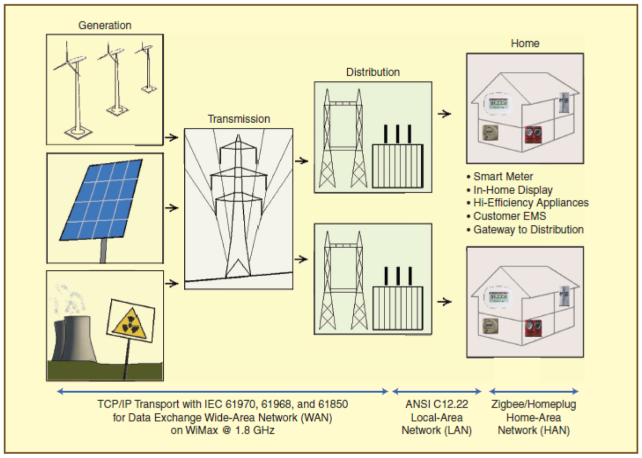


Fig. 6. Standards for potential SG communication network [6].

IV. CONCLUSION

Had the Smart Grid been fully designed and successfully implemented into the electrical infrastructure prior to August of 2003 it is certain that the events would have been different. The microgrid design would have proven helpful to the reactive power issue. It would mean there were more reactive power providers (whether in reserve or dispatched) since each microgrid would have its own cogeneration of renewable resources. The Smart Grid's network of sensors and automatic controls would allow for instantly rerouting power flows and shutting down or turning on generation plants. Research from fields such as nonlinear dynamic systems, artificial intelligence, game theory, and software engineering has led to a general theory of how to design complex systems that adapt to changing conditions, which is the basis for Smart Grid [7]. Ultimately it is heavily sensor based and depends on a similar network topology to modern telecommunications such as internet, wireless, and digital networking (author's opinion). Sensors are important additions when human limitations are at hand. For instance, the issues with the overgrown trees could have been alleviated by sensors supporting encroachment zones, as opposed to dependence on ground crews or flying overhead to check transmission networks. First Energy reportedly patrolled their lines regularly by flying over each transmission line twice a year to check on the condition of the rights-of-way [2] but yet vegetation issues were a major cause of the blackout since they grow fast in the summer. Sensors could have kept reminding crews to clear the lines.

Certain relay issues played a role in the events that transpired too. For instance, the Sammis-Star transmission line tripped because its protective relays saw low apparent impedance, which is depressed voltage divided by abnormally high current, so the relay reacted as if the high power flow was due to a short circuit [2]. However, with Smart Grid technology, many utilities have now deployed model smart RTUs and programmable controllers that can autonomously execute simple processes without first checking with a human controller and that can be reprogrammed at a distance by operators if needed [7]. This means the system response time is much quicker, since information no longer has to wait for the slower SCADA system to receive and react to information from the RTU. Intelligent processors could run diagnostics on the relays to ensure they're operating correctly too. When MISO was having issues with its state model estimator in 2003, operators had to manually update the model so it could recalculate, but that the model was already wrong due to lines that tripped in the time period it took to update. [2]. Smart Grid processors could have gone into control loops to recalculate the state estimator contingency model correctly.

Frequency imbalance didn't cause the blackout but it did cause the cascade. In real-time, generation must equal load, which is basic economics; supply equals demand. Recall that in Smart Grid technology, microgrids are designed to be able to decouple or separate from the grid (forming an island). Microgrids are beneficial because they improve reliability, encourage use of renewable resources, and offer self-healing, active load control, and improved efficiencies [8]. The Task Force determined that FE did not have an adequate under-voltage load shedding program in the Cleveland area [2]. With a microgrid topology that would happen automatically when the microgrid disconnected from the network and the cascade could have been completely avoided. Smart Grid is self-healing because microgrids can be switched to island mode and therefore the users in microgrids will not be affected by outages and recover as soon as the switch is opened [8]. Additionally, visibility is increased by an array of sensors that monitor electrical parameters enabling the system to constantly tune itself to an optimal state. As research continues in the area of Smart Grid it is certain that there will be more discussion on the potential risks of system vulnerability that cyber security issues introduce.

The 2003 Northeast Blackout has set the stage or the plea rather, for a Smart Grid system to modernize the grid. The best solution is a portfolio of technology that Smart Grid seeks to integrate, which includes using multiple generation technologies. The industry is at a place where faster, more reliable technology needs to be implemented within the electric grid, to alleviate issues with interfacing control area operators and provide real time monitoring and self-recovering feasibility for transients or worse.

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