The Anatomy of a Power Grid Blackout

Root Causes and Dynamics of Recent Major Blackouts

IN 1895, THE WESTINGHOUSE COMPANY COMPLETED THE CONSTRUCTION OF THE NIAGARA Falls power station with a capacity of roughly 7.5 MW, produced from hydro turbines, using patents and designs by Nikola Tesla. The following year, General Electric, which had been awarded the contract for the transmission and distribution lines, completed the transmission system necessary to carry the power to the nearby city of Buffalo. This polyphase ac system was perhaps the greatest of its time and one of the first true power systems in the world. Today, the North American power system spans the United States, Canada, and Mexico. This system incorporates tens of thousands of transmission lines, generating stations, transformers, complex power electronic transmission equipment, and myriad automatic control and protection systems that keep this vastly complex system operating 24 hours a day, seven days a week, year after year. Similarly vast and complex power systems span continental Europe, Asia, South America, and other parts of the world. This constant delivery of electrical power is such an integral part of modern human life that it is, for the most part, taken for granted until, suddenly and without prior warning, a blackout occurs, resulting in a complete disruption of power supply to entire regions or countries!

Recently, the Power System Dynamic Performance Committee (PSDPC) of the IEEE Power Engineering Society sponsored a panel session on the subject of the major blackouts of 2003. In addition, the

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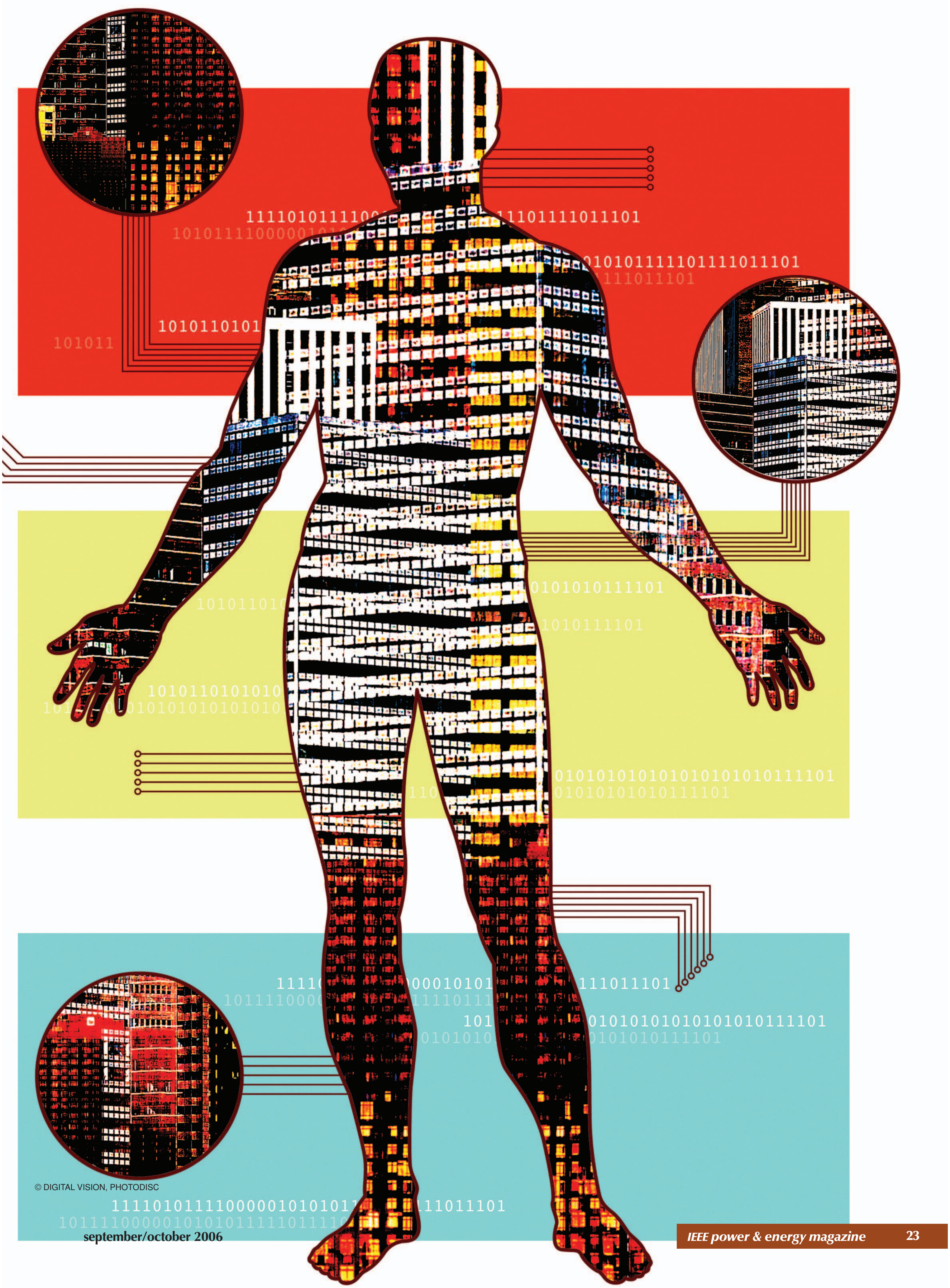

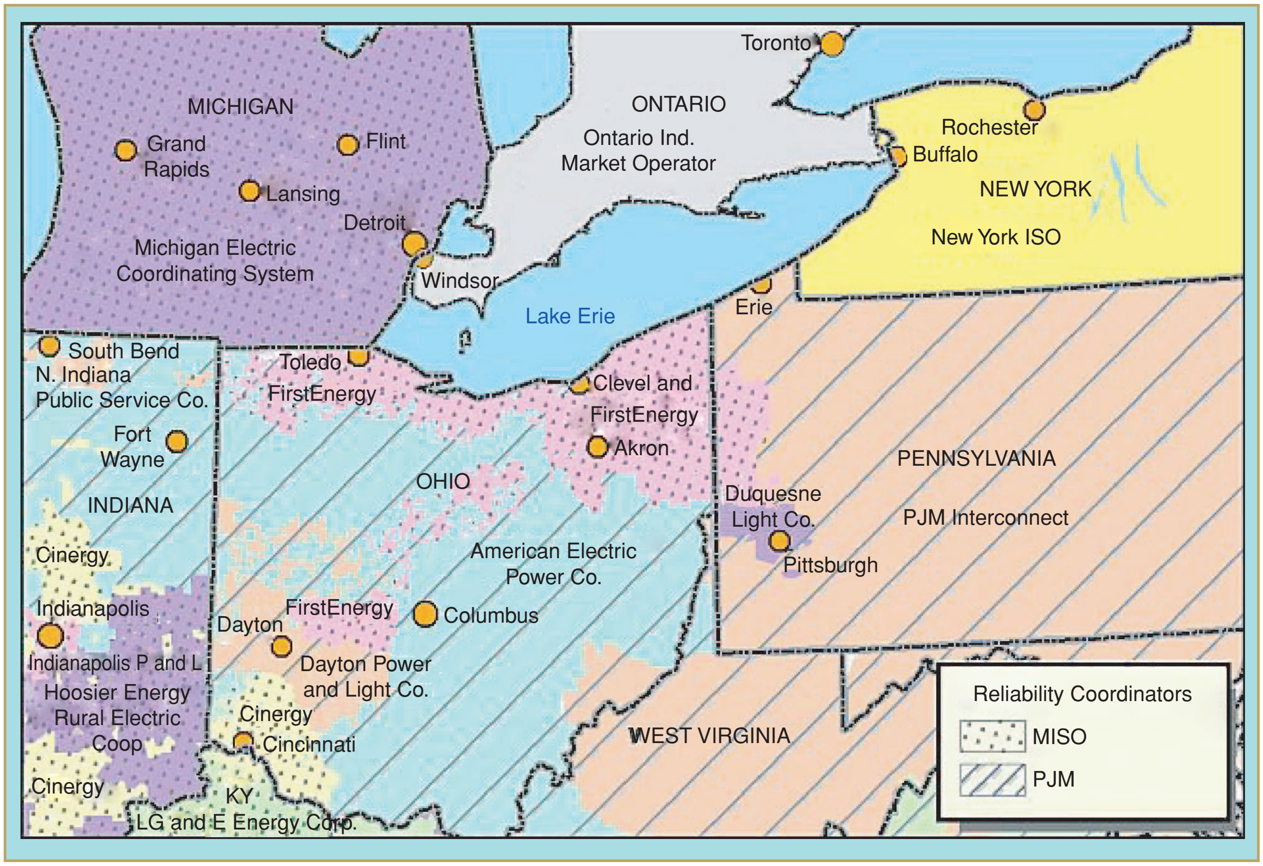

figure 1. The region affected by the U.S.-Canadian blackout of 14 August 2003.

Administrative Committee of the PSDPC prepared a high-level policy-orientated paper on the 2003 blackouts (see "For Further Reading"). This inspired the formation of the current IEEE Task Force on Blackout Experience, Mitigation, and Role of New Technologies, which is presently preparing a comprehensive document on the subject of blackouts.

In this article, we will look at some recent major blackouts and then discuss some of the root causes and dynamics of these events. This will help to identify high-level conclusions and recommendations for improving system dynamic performance and reducing the risk of such catastrophic events.

Major Blackouts of 2003

The U.S.-Canadian blackout of 14 August 2003 affected approximately 50 million people in eight U.S. states and two Canadian provinces. Roughly 63 GW of load was interrupted, equating to approximately 11% of the total load served in the Eastern Interconnection of the North American system, which spans from the central states of the United States to the East Coast and from the eastern Canadian provinces to Florida. During this event, over 400 transmission lines and 531 generating units at 261 power plants tripped. Figure 1 shows the general area affected by this blackout.

Based on the North American Electric Reliability Council (NERC) investigation, prior to the ensuing events that led to the blackout, the system was being operated in compliance with NERC operating policies. However, there were apparent reactive power supply problems in the states of Indiana and Ohio prior to noon on 14 August 2003. The Midwest ISO (MISO) state estimator (SE) and real-time contingency analysis (RTCA) software were inoperative (not functioning properly due to software problems) for most of the afternoon. This prevented MISO from performing proper "early warning" assessments of the system as the events were unfolding. At the FirstEnergy (FE) control center, a number of computer software failures occurred on their energy management system (EMS) software starting at 2:14 p.m. This prevented FE from having adequate knowledge of the events taking place on its own system until approximately 3:45 p.m. This contributed to inadequate situational awareness at FE.

The first major event was the outage of FE's Eastlake Unit 5 generator. Eastlake Unit 5 and several other generators in FE's Northern Ohio service area were generating high levels of reactive power, and the reactive power demand from these generators continued to increase as the day progressed. Such high reactive power loading of generators can be a concern and may lead to control and protection problems. In fact, due to high reactive output, the Eastlake Unit 5 voltage regulator tripped to manual due to overexcitation. As the operator attempted to restore automatic voltage control, the generator tripped. A modern excitation system automatically returns to voltage control when conditions permit. The

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Chamberlin-Harding 345-kV line tripped at 3:05 p.m. in FE's system due to tree contact; the line was only loaded to 44% of summer normal/emergency rating. The Hanna-Juniper 345-kV line loaded to 88% of its summer emergency rating and tripped due to tree contact at 3:32 p.m. This cascading loss of lines continued while little action was being taken to shed load or readjust the system since during this period, due to EMS failures at FE and MISO control centers, there was little awareness of the events transpiring.

The critical event leading to widespread cascading in Ohio and beyond was the tripping of the Sammis-Star 345-kV line at 4:05:57 p.m. The line tripped by the Sammis End Zone 3 relay operating on real and reactive current overload and depressed voltage. Tripping of many additional lines in Ohio and Michigan by Zone 3 relays, or Zone 2 relays set similar to Zone 3 relays, followed. Prior to the Sammis–Star tripping, the blackout could have been prevented by load shedding in northeast Ohio.

At approximately 4:10 p.m., due to the cascading loss of major tie-lines in Ohio and Michigan, the power transfer between the United States and Canada on the Michigan border shifted. That is, power started flowing counterclockwise from Pennsylvania through New York and Ontario and finally into Michigan and Ohio. This huge (3,700 MW) reverse power flow was intended for serving load in the Michigan and Ohio system, which was at this stage severed from all other systems except Ontario. At this point, voltage collapsed due to extremely heavily loaded transmission, and a cascading outage of several hundred lines and generators ensued, culminating in a blackout of the entire region.

In the same year, two other major blackouts occurred in Europe. One of these, occurring on 23 September 2003, unfolded in the Swedish/Danish system. The system was moderately loaded before the blackout, but several system components, including two 400-kV lines and high-voltage dc (HVDC) links connecting the Nordel (power system of the Nordic countries) system with continental Europe, were out of service due to maintenance. Even taking these scheduled outages into account, the system was not stressed.

The first contingency was the loss of a 1,200-MW nuclear unit in southern Sweden due to problems with a steam valve. This resulted in an increase of power transfer from the north. System security was still acceptable after this contingency. Five minutes after this outage, a fault occurred about 300 km from the location of the tripped nuclear unit; these two events were unrelated.

Due to the failure of substation equipment (a disconnector), a double bus-bar fault ensued. This resulted in the loss of a number of lines and two 900-MW nuclear units and, as a consequence, a very high power transfer north to south on the remaining 400-kV line. Consequently, the system experienced voltage collapse leading to the separation of a region of the southern Swedish and eastern Denmark system. In a matter of seconds, this islanded system collapsed in both voltage and frequency, thus resulting in a blackout. The islanded system had only enough generation to cover some 30% of its demand, which was far from sufficient to allow islanded operation. A total of 4,700 MW of load was lost in Sweden (1.6 million people affected) and 1,850 MW in Denmark (2.4 million people affected).

The third major blackout of 2003 occurred in continental Europe on 28 September. This blackout resulted in a complete loss of power throughout Italy. The sequence of events leading to this blackout began when a tree flashover caused the tripping of a major tie-line between Italy and Switzerland. The connection was not reestablished because the automatic breaker controls did not reclose the line; the phase angle difference across the line was too large due to the heavy power import into Italy. This resulted in an overload on parallel transmission paths. Since power was not redistributed quickly and adequately, a second 380-kV line also tripped on the same border (Italy-Switzerland) due to tree contact. This cascading trend continued. In a couple of seconds, the power deficit in Italy was such that Italy started to lose synchronism with the rest of Europe and the lines on the interface between France and Italy tripped due to distance relays (first or second step). The same happened for the 220-kV interconnection between Italy and Austria. Subsequently, the final 380-kV corridor between Italy and Slovenia became overloaded and it tripped too. These outages left the Italian system with a shortage of 6,400 MW of power, which was the import level prior to the loss of the interconnecting lines. As a consequence, the frequency in the Italian system started to fall rapidly and, due to this swift frequency decay, many generators tripped on underfrequency. Thus, over the course of several minutes, the entire Italian system collapsed, causing a nationwide blackout. This was the worst blackout in the history of the Italian nation.

Generalities and Root Causes— The Anatomy of a Blackout

Most major grid blackouts are initiated by a single event (or multiple related events such as a fault and a relay misoperation)

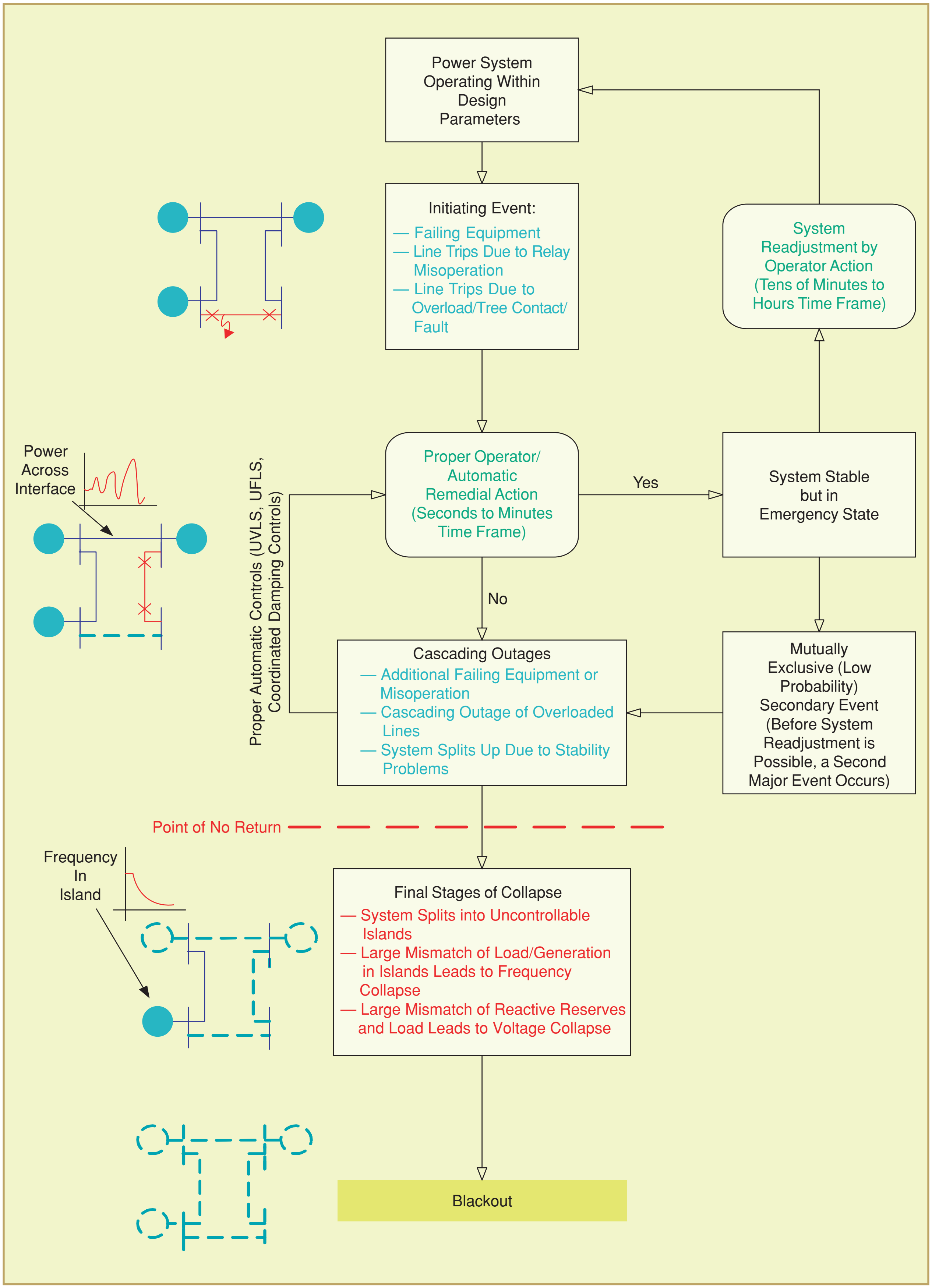

figure 2. General sequence of events leading to a blackout.

that gradually leads to cascading outages and eventual collapse of the entire system. With hindsight, one can often identify means of mitigating the initial event or minimizing its impact to reduce the risk of the ensuing cascading trips of lines and generation. Given the complexity and immensity of modern power systems, it is not possible to totally eliminate the risk of blackouts. However, there are certainly means of minimizing the risk based on lessons learned from the general root causes and nature of these events.

To help visualize some of the interrelationships between events on the system as a blackout unfolds, Figure 2 provides a graphical outline of the general sequence of events. Typically, the blackout can be traced back to the outage of a single transmission (or generation) element. The majority of these events tends to be the result of equipment failure (aging equipment, misoperation of a protective device, etc.) or environmental factors (e.g., tree contact and tripping of a line due to excessive sag on a hot summer day). Human error can also be a contributing factor. If proper planning criteria are followed, most modern power systems are designed to be able to operate safely and in a stable fashion for such single (or multiple common-mode) outages. However, depending on the severity of the event, the system may enter into an emergency state following the disturbance, particularly during peak load hours. Thus, if proper automatic control actions or operator intervention are not taken decisively, the system may be susceptible to further failures and subsequent cascading. Also, though quite rare, it is possible (see, for example, the discussion on the Swedish blackout) to have a second uncorrelated event occur while the system is in this emergency state following an N-1 event, prior to system readjustment.

In the case where proper operator or automatic control actions are not taken, the consequences can be numerous. In the simplest case (e.g., the Italian and North American blackouts discussed above), parallel transmission paths may become overloaded due to a redistribution of power after the initial outage, and thus a process of cascading transmission line outages may ensue. At some point this will lead to dynamic performance issues. That is, the increasing electrical distance between load and generation (as ac transmission lines trip) may lead to a number a factors.

- ✔ *Transient angular instability*: The initial large disturbance (e.g., transmission system fault) will lead to deviations in generator rotor angles. If this is then followed by inadequate electrical coupling between groups of generators (due to the loss of transmission lines), it may lead to a lack of synchronizing power and thus an inability for generators in different regions of the system to keep in sync with each other. The observed response is a continuously growing angular shift between groups of generators. As the two regions separate in angle, the voltage in between the two regions will be depressed. Such depressed voltage may lead to transmission line protective relays tripping additional lines and, thus, possible eventual severing of all ac transmission paths between the two regions. Out-of-step relays may also be used to deliberately sever ties between the two systems in the event of transient instability. This phenomenon occurs within a few seconds.
- ✔ *Growing power oscillations (small-signal instability)*: In this case, the weakening of the transmission system, coupled with high power transfer levels, leads to uncontrolled growing electromechanical oscillations between groups of generators. The observed response is an uncontrolled growing oscillation in power on transmission corridors until, once again, protective relays result in further partitioning of the system. This phenomenon may take several seconds to tens of seconds to unfold. Figure 3 shows an example of this phenomenon.
- ✔ *Voltage instability or collapse*: In some cases, particularly during peak system load conditions and where air-conditioning loads dominate, transient voltage instability may occur. Transient voltage instability is a very fast phenomenon due to stalling of motor load. In most cases, however, voltage collapse may take several minutes to unfold.

If unchecked, any one of these unstable dynamic phenomena may lead to partitioning of the system into smaller islands of load and generation. This can then further exacerbate the problem due to unstable and uncontrolled frequency response due to large imbalance between load and generation in these islands. Eventually, a point of no return is reached at which time the multitude of cascading events and their rapid succession becomes unmanageable and a rapid chain reaction of load and generation tripping leads to the ultimate blackout.

One of the other causes of cascading is often the indiscriminating way in which protective devices and relays operate. For example, one of the primary means of protecting extra-high-voltage transmission lines is through the use of distance relays, which look at apparent impedance as a means of detecting a fault. In many of the blackouts in North America, such relays have initiated line tripping due to heavy load and depressed voltage conditions, which result in apparent impedances that fall into the Zone 3 settings of line relays. Thus, the relay trips the line since it believes a fault has occurred, while in actuality there is no fault condition. This then further increases loading on parallel lines, and the process continues, resulting in a cascading sequence of line outages. With the advent of digital equipment, it is incumbent on the industry to consider research into practical means of performing protective functions in a more discriminating manner.

Means of Reducing the Risk of a Blackout

It is, of course, not possible to achieve 100% reliability and security of a power system. Human error or acts of nature (ice storms, hurricanes, etc.) are facts of life that cannot be eliminated. The goal, instead, should be to maintain an adequate level of system reliability and security to minimize the risk of major blackouts resulting from cascading outages emanating from a single disturbance. Clearly, the most straightforward way is to minimize the risk of inadvertent disturbances by mitigating, as far as possible, the root cause of system disturbances. That is, through

- ✔ prioritized replacement of legacy power plant and transmission control and/or protection equipment with modern equipment and designs; this both helps to reduce the risk of disturbances caused by failing equipment and, in many cases, can directly improve reliability (for example, replacing an old main and transfer substation design with a breaker-and a half design)
- ✔ regular maintenance, evaluation, and testing of power plant and substation equipment to ensure that the equipment is maintained in a good condition and is operating within design parameters; in addition to prolonging equipment life through proper maintenance, testing and maintenance helps to identify inadvertent or improper settings on control and protection systems, thus minimizing the risk of disturbances resulting from the misoperation of devices.

In addition to the above preventative measures, there are also active measures that can be taken to prevent cascading when a single major disturbance does occur. A wide range of established, as well as new and emerging, technologies can assist in significantly minimizing the impact of an event and, thus, help to mitigate the risk of widespread blackouts. Some of the established and newer technologies include

- ✔ coordinated emergency controls (such as special protection systems, undervoltage load shedding, and underfrequency load shedding)
- ✔ flexible ac transmission systems (FACTS) and HVDC
- ✔ online dynamic security assessment
- ✔ real-time system monitoring and control.

Some emerging technologies that may be equally as effective are

- ✔ adaptive relaying
- ✔ distributed generation technologies
- ✔ wide-area monitoring and control
- ✔ risk-based system security assessment (for planning and real-time applications).

Most of these technologies are discussed in the subsequent articles and in some of the literature provided below as further reading.

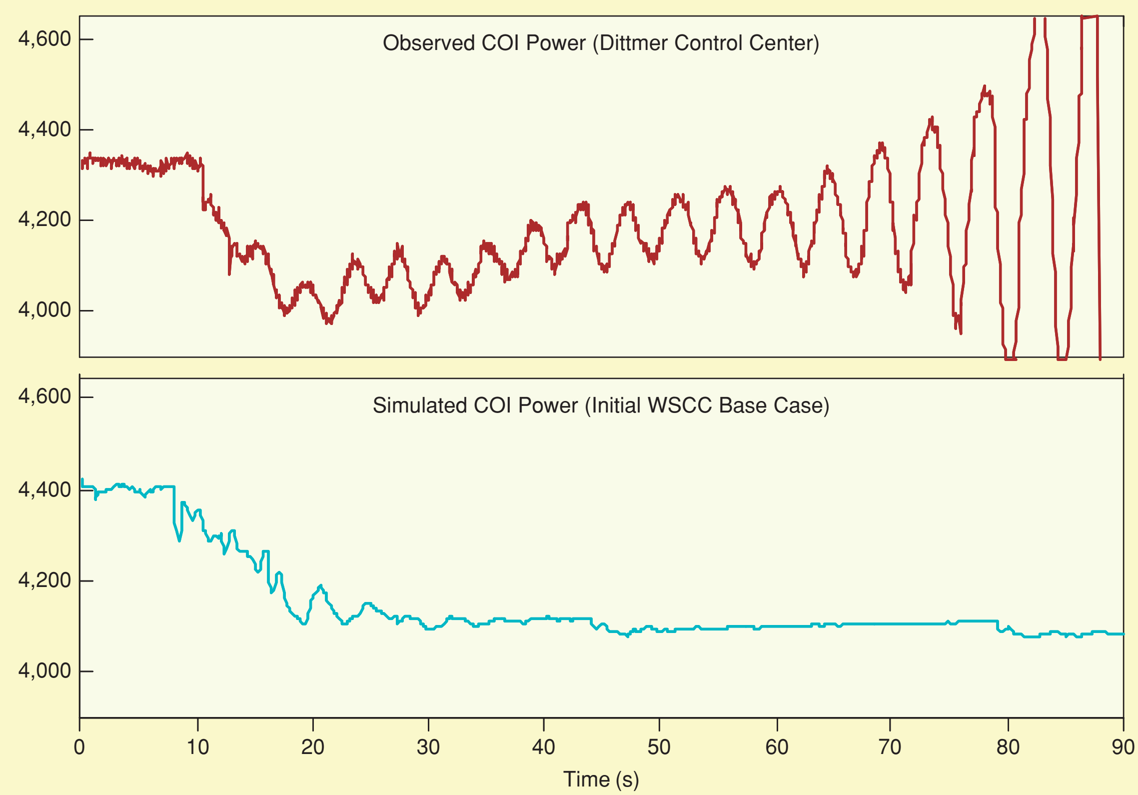

figure 3. Growing power oscillations that occurred during the 10 August 1996 blackout in the North American Western-Interconnected system: (a) actual recorder power oscillations on the California-Oregon Interface (COI) and (b) the simulated event based on the initial Western System Coordinating Council (WSCC) power system model database. This disparity was the motivation of much modeling and testing activity that has since continued in the now Western Electricity Coordinating Council (WECC). (Figure courtesy of Bonneville Power Administration.)

Conclusions

Blackouts are major catastrophic failures in large interconnected power systems. Predicting the occurrence of such phenomena is difficult at best. When they occur, however, the socioeconomic impact is devastating. Some of the clear root causes for these events are

- ✔ a lack of reliable real-time data
- ✔ a lack of time to take decisive and appropriate remedial action against unfolding events on the system
- ✔ increased failure in aging equipment
- ✔ a lack of properly automated and coordinated controls to take immediate and decisive action against system events in an effort to prevent cascading.

Many of these problems may be driven by changing priorities for expenditures on maintenance and reinforcement of the transmission system. Nonetheless, with proper and prudent expenditure, the appropriate technologies can be found to address these root causes. In addition, it is incumbent on policymakers to ensure that reliability standards are made mandatory and enforceable, backed by meaningful and effective penalties for noncompliance. Furthermore, reliability standards should be reviewed periodically, taking into account experiences from major system incidents and evolving technologies such as those described in the other theme articles in this issue of *IEEE Power & Energy Magazine*. At a regulatory body level, clarification should be provided on the need for expenditure and investment for bulk system reliability and how such expenditure will be recoverable through transmission rates.

For Further Reading

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Biographies

Pouyan Pourbeik received his B.E. and Ph.D. degrees in electrical engineering from the University of Adelaide, Australia, in 1993 and 1997, respectively, and is a registered professional engineer in the state of North Carolina. He is an executive consultant with EPRI Solutions, Inc., where he is responsible for leading and performing technical studies research related to all aspects of power generation and transmission for utility clients in North America and overseas. Before joining EPRI, he worked for ABB and prior to that GE Power Systems. He is presently the chair of the IEEE Power Engineering Society (PES) Power Systems Stability Subcommittee and convener of the CIGRÉ WG C4.6.01 on Power System Security Assessment. He is a Senior Member of the IEEE and serves as the secretary of the IEEE Task Force on Blackout Experience, Mitigation, and Role of New Technologies.

Prabha S. Kundur received a Ph.D. in electrical engineering from the University of Toronto and has over 35 years of experience in the electric power industry. He is currently the president and chief executive officer of Powertech Labs, Inc., the research and technology subsidiary of BC Hydro. Prior to joining Powertech in 1993, he worked at Ontario Hydro for nearly 25 years and was involved in the planning, design, and operation of power systems. He has chaired numerous committees and working groups of the IEEE Power Engineering Society (PES) and was elected as a Fellow of the IEEE in 1985. He is currently the PES vice president for Education/Industry Relations Activities; chair of the IEEE Task Force on Blackout Experience, Mitigation, and Role of New Technologies; and also the chair of the CIGRÉ Study Committee C4. He is the author of the book *Power System Stability and Control* (McGraw-Hill, 1994) and is the recipient of the 1997 IEEE Nikola Tesla Award, the 1999 CIGRÉ Technical Committee Award, and the 2005 IEEE PES Charles Concordia Power System Engineering Award.

Carson W. Taylor joined Bonneville Power Administration in 1969 after earning degrees from the University of Wisconsin and Rensselaer Polytechnic Institute, New York. His interests include power system control and protection, system dynamic performance, ac/dc interactions, and power system operations and planning. He retired in January 2006 from a BPA principal engineer position in Transmission Operations and Planning. He is a member of the U.S. National Academy of Engineering. He is a Fellow of the IEEE and past chair of the IEEE Power System Stability Controls Subcommittee. He is a distinguished member of CIGRÉ and convenor of three CIGRÉ task forces. He has instructed many industry short course and authored the book *Power System Voltage Stability*. He is the cochair of the present IEEE Task Force on Blackout Experience, Mitigation, and Role of New Technologies. p&e