Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance

G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik, J. Sanchez-Gasca, R. Schulz, A. Stankovic, C. Taylor, and V. Vittal

***Abstract*—On August 14, 2003, a cascading outage of transmission and generation facilities in the North American Eastern Interconnection resulted in a blackout of most of New York state as well as parts of Pennsylvania, Ohio, Michigan, and Ontario, Canada. On September 23, 2003, nearly four million customers lost power in eastern Denmark and southern Sweden following a cascading outage that struck Scandinavia. Days later, a cascading outage between Italy and the rest of central Europe left most of Italy in darkness on September 28. These major blackouts are among the worst power system failures in the last few decades. The Power System Stability and Power System Stability Controls Subcommittees of the IEEE PES Power System Dynamic Performance Committee sponsored an all day panel session with experts from around the world. The experts described their recent work on the investigation of grid blackouts. The session offered a unique forum for discussion of possible root causes and necessary steps to reduce the risk of blackouts. This white paper presents the major conclusions drawn from the presentations and ensuing discussions during the all day session, focusing on the root causes of grid blackouts. This paper presents general conclusions drawn by this Committee together with recommendations based on lessons learned.**

***Index Terms*—Blackouts, power system control, power system dynamic performance, power system stability.**

I. Introduction

THIS paper contains a summary of the presentations made during the all day panel session on Major Grid Blackouts of 2003 in North America and Europe, held on June 8, 2004 at the IEEE Power Engineering Society General Meeting in Denver, Colorado. The presentations [1]–[10] of the session are available on the website of the IEEE PES Power System Dynamic Performance Committee,[1] the parent Committee for the two Subcommittees that sponsored the all-day panel session.

Section II of this paper presents a brief summary of the causes of the three major blackouts. Section III presents a summary of the recommendations made by the panelists and through general discussion at the panel session. Section IV presents a brief description of new and evolving technologies that may be used to reduce the risk of major system blackouts in the future. Finally, Section V presents overall conclusions and recommendations.

II. What Caused the Blackouts?

This section provides a summary of the cause of each of the three recent blackouts, with a primary emphasis on the North American blackout.

A. Blackout of August 14, 2003 in North America [2], [11]

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

Based on the North American Electric Reliability Council (NERC) investigation [2], [11], prior to 15:05 Eastern Daylight Time, the system was being operated in compliance with NERC operating policies. However, there were significant reactive power supply problems in the states of Indiana and Ohio prior to noon. The Midwest ISO (MISO) state estimator (SE) and real time contingency analysis (RTCA) software were inoperative (not functioning properly due to software problems) from 12:15 to 16:04. This prevented the 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 14:14. This prevented FE from having adequate knowledge of the events taking place on its own system until approximately 15:45. This contributed to inadequate situational awareness at FE.

The first major event was the outage of FE's Eastlake unit 5 generator at 13:31. 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 [12]. High generator reactive power loading means limited margin to support the system for potential outages. Also, such high reactive loading may cause control and protection problems. In fact, due to high reactive output, the Eastlake unit 5 voltage regulator tripped to manual because of over-excitation.

Manuscript received January 28, 2005; revised June 20, 2005. Paper no. TPWRS-00056-2005.

The authors are the members of the Administrative Committee of the Power System Dynamic Performance Committee, IEEE Power Engineering Society. Chair: G. Andersson, Secretary: N. Hatziargyriou, Immediate past Chair: P. Kundur, Vice-Chair: J. Paserba, Past member: C. Taylor.

Digital Object Identifier 10.1109/TPWRS.2005.857942

[1][Online] Available at: http://psdp.ece.iastate.edu/#Recent_Panel_Sessions

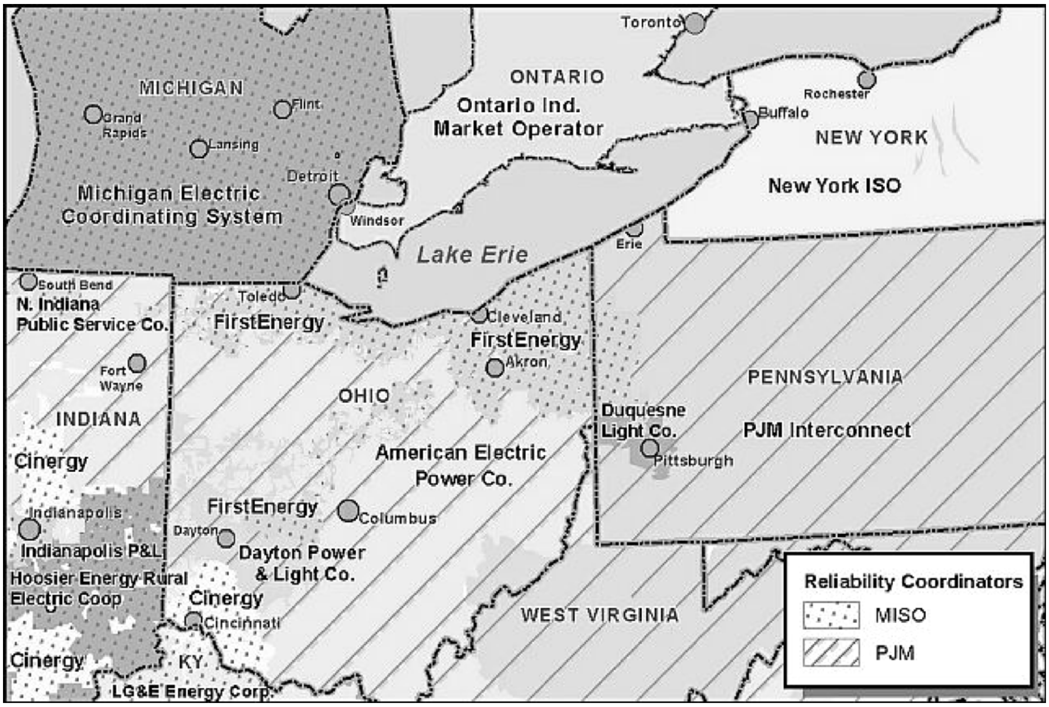

Fig. 1. Region affected by the U.S.-Canadian blackout of August 14, 2003.

As the operator attempted to restore automatic voltage control the generator tripped. A modern excitation system automatically returns to voltage control when conditions permit. This suggests the need for prioritized replacement of old control and protection with modern digital equipment.

The Chamberlin–Harding 345-kV line tripped at 15:05 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 15:32. The Star–Canton 345-kV line loaded to 93% of its rating and tripped due to tree contact at 15:41. During this period due to EMS failures at FE and MISO control centers, no proper operational actions were being taken due to lack of situation awareness. This cascading loss of lines continued while little load was being shed or lost.

The critical event leading to widespread cascading in Ohio and beyond was the tripping of the Sammis–Star 345-kV line at 16:05:57 [11]. The line tripped by 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.

In the past, undesirable zone 3 relay and other generation and transmission backup relay operations have contributed to blackouts such as the November 9, 1965 northeast U.S./Canada blackout, the July 2, 1996 western U.S. blackout, and the March 11, 1999 Brazil blackout. Following the 1996 western outages, NERC approved an un-enforced guide in its Planning Standards (III.A.G17: "applications of zone 3 relays with settings overly sensitive to overload or depressed voltage conditions should be avoided where possible."). NERC is now pursuing this more seriously to investigate the concerns related to zone 3 relays. Several options including removal of zone 3 relays are available to prevent operation of short-circuit protection due to overloads [13].

At approximately 16:10, due to the cascading loss of major tie lines in Ohio and Michigan, the power transfer between the U.S. and Canada on the Michigan boarder shifted. That is, power started flowing counterclockwise from Pennsylvania, through New York and then Ontario and finally into Michigan and Ohio. This huge (3700 MW) reverse power flow was 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.

The U.S.-Canada Power System Outage Task Force report [2], [11] indicates that the primary causes were as follows.

1) **Inadequate understanding of the system:** The report asserts that FE failed to conduct necessary long-term planning studies, sufficient voltage stability analysis of the Ohio control area and used operational voltage criteria that did not reflect actual system behavior and needs. Furthermore, the East Central Area Reliability Coordination Agreement (ECAR) did not conduct sufficient independent review of FE's analysis and some of the NERC planning standards were sufficiently ambiguous such that they were interpreted in a way that resulted in inadequate reliability for system operation.
2) **Inadequate level of situation awareness:** The report asserts that FE failed to ensure security of its system after significant unforeseen contingencies due to the failure of various EMS system components.
3) **Inadequate level of vegetation management (tree trimming):** The failure by FE to adequately manage tree

growth in its transmission rights-of-way resulted in the outage of three 345-kV lines and one 138-kV line.

4) **An inadequate level of support from the Reliability Coordinator (RC):** Due to the failure of the MISO state-estimator and other real-time data deficiencies, the MISO did not become aware of FE's system problems early enough and did not provide assistance to FE. Also, PJM[2] and MISO did not have in place an adequate level of procedures and guidelines on how and when to coordinate a security limit violation observed by one of them in the other's area, due to a contingency near their common boundary.

B. Blackout in Southern Sweden and Eastern Denmark—September 23, 2003 [3]

The system was moderately loaded before the blackout but several system components, including two 400-kV lines and HVDC links connecting the Nordel system with continental Europe, were out of service due to maintenance. During this period of the year a significant amount of maintenance activities take place before the peak load period during the winter. Even taking these scheduled outages into account the system was not stressed.

The first contingency was the loss of a 1200-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 away from the location of the tripped nuclear unit.

Due to the failure of a piece 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 and thus resulted in a blackout. The islanded system had only a total generation to cover some 30% of its demand, which was far from sufficient to allow islanded operation. A total of 4700 MW of load was lost in Sweden (1.6 million people affected) and 1850 MW in Denmark (2.4 million people affected).

C. Italian Blackout of September 28, 2003 [4], [5], [14]

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 [14]. The connection was not re-established because the automatic breaker controls refused to re-close 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 a parallel path. 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 loose 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 too tripped. These outages left the Italian system with a shortage of 6400 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. The frequency decay was not controlled adequately to stop generation from tripping due to 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 nation.

III. RECOMMENDATIONS MADE BY THE PRESENTERS AND DURING THE PANEL DISCUSSION

The recommendations made by the presenters during the session were as follows.

A. Data Management Issues [7]

To facilitate a smoother and more expeditious process for data gathering and processing in the aftermath of a blackout, the following recommendations were made.

- Improve the calibration of recording instruments, especially in establishing time synchronization.
- Establish pre-defined data reporting requirements and standardized data formats.
- Establish pre-defined commercial logistics, such as confidentiality agreements.
- Establish an infrastructure to support a centralized blackout investigation.
- Automate the means of disturbance reporting.

B. Disturbance Monitoring [8]

To facilitate better insights into the cause of blackouts and enable detailed postmortem analysis, adequate, and appropriate disturbance monitoring is required. This has been achieved to some extent in the development of the wide area measurement systems (WAMS [8]). Some recommendations were given as to how to improve these systems.

- Refine the process for integration, analysis, and reporting of WAMS data. This must also include the development and support of staff and resources.
- Establish a WAMS Website to allow the free exchange of WAMS data, documents, and software and thus promote its development.
- Extend the collection of benchmark events and dynamic signatures to determine the range of normal system behavior.
- Perform related studies (including eigenanalysis) to assist proper interpretation of observed system behavior.
- Fully utilize the capabilities often available in modern HVDC and/or FACTS equipment to directly examine system response to test inputs.

[2]PJM is a regional transmission organization (RTO). It coordinates the transmission of electricity in all or parts of Delaware, Illinois, Maryland, New Jersey, Ohio, Pennsylvania, Virginia, West Virginia, and the District of Columbia.

C. Recommendations From the Joint U.S. and Canadian Task Force for the North American Blackout [2], [11]

The joint U.S. and Canadian Task Force made a list of recommendations following the detailed investigation of the August 14th event. A summary of the key points discussed during the panel session and presented in [2], [11] are listed below.

- Reliability standards should be made mandatory and enforceable, with penalties for noncompliance.
- A regulator-approved funding mechanism should be developed for NERC, and the regional reliability councils, to ensure their independence from the utilities that they oversee.
- At a federal policy level, clarification is needed on expenditures and investments for bulk system reliability (including investments in new technologies) and how such expenditure will be recoverable through transmission rates.
- Track implementation of recommended actions to improve reliability.
- Operators who initiate load shedding pursuant to approved guidelines should be shielded against liability or retaliation.
- Improve the near-term and long-term training and certification requirements for operators, reliability coordinators, and operator support staff.
- Evaluate and adopt better real-time tools for operators and reliability coordinators.
- Strengthen reactive power and voltage control practices in all NERC regions.
- NERC should reevaluate its existing reliability standards development process and accelerate the adoption of enforceable standards.
- Develop enforceable standards for transmission line ratings.
- Employ automatic load shedding.
- Resolving issues related to zone 3 relays (see Section II-A).

D. International Perspective and Recommendations [3]–[5], [9], [10], [15]

Presenters from Sweden, Italy, Brazil, and Japan also spoke of their experience with recent blackouts and presented the lessons learned. Their recommendations and observations are summarized below.

- Large disturbances often stem from a sequence of interrelated events that would otherwise be manageable if they appeared alone. The cascading often results from equipment failure or poor coordination. Thus, the improvement of existing substations and other equipment through refurbishing, constant inspection, and maintenance, and replacement of critical components is vital to the prevention of cascading events.
- Reliability standards applied in power system studies should be constantly evolving in accordance to the requirements of the grid and international state-of-the-art practices and technological developments.
- The use and enhancement of special protection systems can be quite effective at times in preventing cascading outages.
- The application of automatic controls such as automatic voltage regulators, and where applicable power system stabilizers, should be mandatory for generators.
- It is of vital importance to enforce and constantly encourage training programs for system operators and their supporting staff.
- The lessons learned from past mistakes must be incorporated into new procedures as well as using such lessons learned to help develop new and improved technologies for system control and monitoring.
- Normal planning studies cannot capture all of the possible scenarios that may lead to a blackout condition, due to the vast number of possible uncertainties and operating actions.
- Ensure the redundancy and reliability of remote control and telecommunication devices.
- Rapid system restoration is extremely important in order to minimize the impact of a blackout on society [31]. Thus, means should be put into place to measure and reduce restoration times. System operators should be given regular refresher training and live drills on system restoration to ensure that they remain familiar with restoration procedures and best practices. This issue will be explored in greater detail by a task force recently established by the Power System Dynamic Performance Committee.
- Data management and dissemination is also an important consideration. Procedures should be put into place to quickly collect and disseminate information in the aftermath of a major blackout to both facilitate postmortem analysis and informing the public, media and authorities of the probable causes and corrective actions being taken.
- Specific attention should be given to voltage stability. Proper reactive power management, having under voltage load shedding schemes to protect against severe disturbances and proper deployment of shunt reactive compensation are key for ensuring system reliability.

Fig. 2 shows the voltage profile in northern Ohio before the outages that eventually lead to the major system blackout. The profile is from the northwest (Detroit area) to the southeast (close to Pittsburgh). As recommended in two of the presentations [6], [10], a high, relatively flat voltage profile greatly improves reliability—for example, 1.03 per unit (or 355 kV in Fig. 2). It is worth noting that following a massive blackout in 1987, Tokyo Electric Power Company adopted a voltage schedule for heavy load conditions of maximum voltage (550 kV) at power generating stations and 535 kV at network substations. Presently, power plant controls to tightly regulate transmission side voltage have been demonstrated and are available [10], [16]. Such controls can further enhance voltage stability.

With regard to power system dynamic performance a poor voltage profile, even for normal conditions, affects reliability as follows.

1) Causes generators to operate near limits with reduced reactive power reserves for contingencies.
2) Increases transmission reactive power losses.

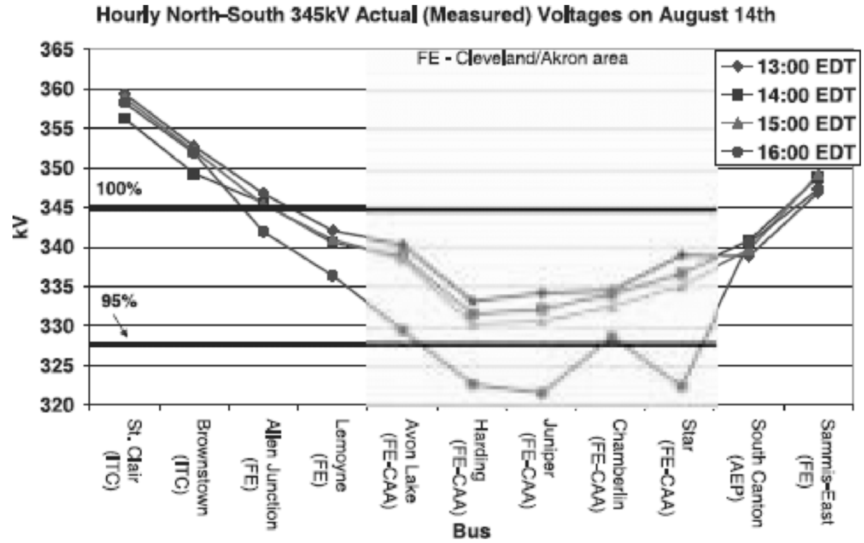

Fig. 2. Voltage profile in northern Ohio prior to blackout.

3) Low voltages increase I^2R heating of transmission lines by a $1/V^2$ factor, and contributes to transmission lines sagging into trees.

IV. New and Emerging Technologies to Assist in Power System Security

To maintain power system reliability and security at 100% is not practical. Whether due to human error or acts of nature, disturbances are a fact of life. What is necessary is to pursue operating strategies, through analysis and training, and new control strategies through technological advancements, in order to minimize the risk of major blackouts and cascading outages due to a single disturbance. Of course, there must always be a balance between improved system security and increased capital investment. Prioritized replacement of legacy power plant and transmission control and protection equipment with modern digital equipment is one suggestion.

A wide range of new and emerging technologies could assist in significantly minimizing the occurrence and impact of widespread blackouts. These include:

- risk-based system security assessment;
- coordinated emergency controls;
- on-line dynamic security assessment;
- adaptive relaying;
- real-time system monitoring and control;
- distributed generation technologies;
- FACTS and HVDC.

The general industry practice for system security assessment has been to use a deterministic approach. The power system is designed and operated to withstand the loss of any single element proceeded by a single-, double-, or a three-phase fault. This is usually referred to as the $\mathrm{N}-1$ criterion because it examines the behavior of an N-component grid following the loss of any one of its major components. One of the main limitations of this approach is that it does not consider multiple outages. The other major limitation is that all security-limiting scenarios are treated as having the same degree of risk. Widespread blackouts are rarely the result of a single catastrophic disturbance causing collapse of an apparently secure system. They are brought about by a combination of events resulting in multiple outages that stress the network beyond its capability. This is abundantly clear from the blackouts described in this paper. There is, therefore, a need to consider multiple outages and to use risk-based security assessment, which accounts for the probability of the system becoming unstable and its consequences. This approach is computationally intensive but is feasible with today's computing and analysis tools.

An effective way to minimize the consequences of multiple outages and prevent widespread blackouts is to use a comprehensive set of well coordinated emergency controls, such as generation tripping, load shedding, transient excitation boosting, transformer tap-changer blocking and controlled system separation. The emergency control schemes should be judiciously chosen so as to protect against different scenarios and act properly in complex situations [17]–[19].

The traditional approach to determining system operating limits has been based on off-line dynamic security analysis tools. There is clearly a need to use on-line dynamic security assessment (DSA) tools. Practical on-line DSA tools with the required accuracy, computational speed and robustness have been developed [20]. They are capable of automatically determining all potentially critical contingencies, assessing security limits for all desired energy transactions, and determining remedial control measures to ensure sufficient stability margin.

One of the factors that contribute to cascading outages following major disturbances is seen to be unnecessary tripping of system components that were not faulted due to the indiscriminate operation of the associated protective relaying. The problem is caused by the inability of conventional relays with fixed settings to discriminate between truly faulted conditions and system dynamic conditions. This problem may be overcome by the use of adaptive relaying with settings that adapt to the real-time system states as the system conditions change [21].

Other adaptive controls such as adaptive islanding [22] and automatic load shedding [23] may also provide significant improvements to system reliability.

The above descriptions on recent blackouts make evident that one of the primary causes of cascading outages was due to a lack of information on system conditions and a lack of readiness to take action. This particular issue can be addressed with better monitoring and intelligent control. One emerging methodology for such intelligent controls is referred to as wide-area monitoring and control [24], [25]. Wide-area stability/voltage control may be used for generator or load tripping, or mechanically or power electronic switched reactive compensation devices [12], [26].

This concept of a dynamic wide-area monitoring system provides additional real-time information like voltage angles, thermal stresses of lines and stability of transmission corridors. Through better real time knowledge of the actual network condition, emergency conditions can be more easily recognized and possibly avoided or during their occurrence better analyzed and remedial actions taken in a quicker and more controlled fashion.

Flexible ac Transmission Systems (FACTS) have a number of benefits. Shunt devices such as static VAr compensators (SVCs) can be used to provide significant improvements in voltage control particularly in regions where old generation assets are being retired leaving large load pockets with little to no dynamic reactive support in the immediate vicinity [27], [28]. Another family of static compensators (STATCOM) is based on voltage sourced converter technology. Under certain system conditions, these devices present additional benefits since once at their reactive limit a STATCOM is a constant current device, while an SVC tends to be a constant impedance device. Since a STATCOM is typically a higher cost item than a comparable thyristor based SVC, the application should justify the additional cost. Fast automatic switching of large shunt capacitor banks can also improve voltage stability [29]. Series devices such as thyristor controlled and conventional series capacitors help to improve transient stability margins on long extra-high voltage transmission corridors. More traditional devices such as phase-shifting transformers can also often be applied for controlling power flow on parallel paths. Emerging technologies such as Unified Power Flow Controllers (UPFC) can also control power flow on parallel transmission corridors, though UPFC is yet to be established as a commercially viable technology.

The new family of HVDC technology uses voltage source converters (VSC). They can be used with easy to install polymer cables, which are lead and oil free. This enables environmentally friendly new transmission, which may reduce the time required to obtain transmission line construction permits. In addition, voltage source converters provide full independent controllability of active and reactive power. Forced commutation in a VSC means that this type of HVDC system can black-start an islanded region of the system and can be applied in very weak systems. Due to the controllability of power flow, an HVDC system will not be overloaded in an emergency system condition, which significantly reduces the risk of cascading outages. The ability for reactive power control, available with VSC, also significantly improves voltage regulation and control thereby improving system stability by reducing the risk of voltage collapse.

Distributed generation (DG) technologies can potentially improve reliability and security of supply. Most of these generation units are interfaced by power electronic converters, which can support active and reactive power locally and even provide local black-start functions, if appropriate regulatory and market conditions permit it. It should be emphasized that DG is connected to the medium-voltage and low-voltage networks providing generation support where it is most needed, in case of higher voltage network failures. Line overloading at higher voltage levels can therefore be potentially relieved during the critical restoration phase [30]. However, the volatility or limitations of the energy sources (wind, sun), the link to industrial process for co-generation and the inability to control frequency and voltage (depending on the type of generation technology) may often limit the contribution of the associated forms of distributed generation in very perturbed situations. It must be noted that leading edge technologies (such a four-quadrant voltage-source converters), when used to connect distributed generators to the grid, can offer benefits such as voltage control. Moreover, frequency control is possible, if islanded operation is allowed. The potential for distributed resources to provide support at lower voltage levels needs to be recognized in the development of interconnection standards for distributed generation. An excellent step in the right direction is taken in the P1547.4 "Draft Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems." This supplemental guide to the IEEE Std 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems" explicitly discusses the utilization of distributed resources in islanded operation including the ability to separate from and reconnect to the bulk power system. There are, of course, significant challenges to realizing the full potential benefits of distributed generation. First, state of the art technologies need to be applied to allow control action that is beneficial to system reliability and secondly regulatory and market rules must help to facilitate their integration into the bulk power grid.

As emphasized in Section III, another aspect for network security is the reliability of the power plant and substation components (for example as described in Section II-B., one of the initiating events for the Swedish blackout was the failure of a disconnect switch.). New systems such as gas insulated switch-gear (GIS) and automated substation control and protection, integrated in a fully automated substation are leading edge technologies that focus on increased reliability while reducing the size of and number of components in a substation. The reduction in components translates into reduced modes of failure and maintenance cycles, thus increasing reliability. Full plant/substation automation eliminates the potential for human error and increases safety margins. In addition, replacement of old air insulated switchgear with modern equipment together with modified substation layouts can significantly improve network reliability.

In conclusion, there are many new and emerging technologies available presently, and in the near future, that may be utilized to support a higher level of reliability and improved system controllability.

V. General Conclusions and Recommendations

Based on the summary of recent events presented here, one can see a general trend in all of these recent blackouts, namely:

- a lack of reliable real-time data;
- thus, a lack of time to take decisive and appropriate remedial action;
- increased failure in aging equipment;
- a lack of properly automated and coordinated controls to take immediate and remedial 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. We thus see the following four policy level recommendations as key to improving system reliability in order to reduce the risk of blackouts in the future.

1) Reliability standards should be made mandatory and enforceable. These should be backed by meaningful and effective penalties for noncompliance with the standards.
2) Reliability standards should be reviewed periodically, taking into account experiences from major system incidents and evolving technologies such as those described in Section IV.
3) At a regulatory body level, clarification should be provided on the need for expenditure and investment for bulk system reliability (including investments in new technologies) and how such expenditure will be recoverable through transmission rates.
4) At a regulatory body level, there should be continued promotion of ongoing industry and government funded research in the discipline of power systems engineering to meet the challenges of the ever growing and complex power grids around the world.

The above recommendations are general policy level recommendations. A list of more detailed, specific and technical recommendations are given in Section III.

Acknowledgment

The Administrative Committee of the Power System Dynamic Performance Committee of the IEEE Power Engineering Society would like to gratefully acknowledge the effort of all the presenters at the all day panel session on the Major Grid Blackouts of 2003 in North America and Europe. In alphabetical order, the presenters were A. Berizzi, N. B. Bhatt, S. Corsi, J. E. Dagle, P. Gomes, J. F. Hauer, S. Imai and S. Larsson. The morning and afternoon sessions were chaired by P. Kundur and C. W. Taylor, respectively. Without the dedication and hard work of all these individuals, the panel session would not have been possible. We are truly grateful to all of them. Finally, the authors would like to thank Dr. C. Rehtanz for some fruitful discussions regarding new technologies.

References

[1] P. Kundur, "Power grid blackouts," presented at the IEEE PES General Meeting, Denver, CO, 2004.
[2] N. B. Bhatt, "August 14, 2003 U.S.-Canada blackout," presented at the IEEE PES General Meeting, Denver, CO, 2004.
[3] S. Larsson and E. Ek, "The blackout in Southern Sweden and Eastern Denmark, September 23, 2003," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[4] S. Corsi and C. Sabelli, "General blackout in Italy Sunday September 28th, 2003, h 03:28:00," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[5] A. Berizzi, "The Italian 2003 blackout," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[6] C. Taylor, "Preventing blackouts," presented at the IEEE PES General Meeting, Denver, CO, 2004.
[7] J. E. Dagle, "Data management issues associated with the August 14th, 2003 blackout investigation," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[8] J. F. Hauer, N. B. Bhatt, K. Shah, and S. Kolluri, "Performance of WAMS East in providing dynamic information for the North East blackout of August 14, 2003," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[9] P. Gomes, "New strategies to improve bulk power systems security: Lessons learned from large blackouts," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[10] S. Imai, "TEPCO observations on August 14 blackout and recommendations to prevent future blackouts based on TEPCO's experience," presented at the IEEE PES General Meeting, Denver, CO, 2004.
[11] U.S.-Canada Power System Outage Task Force. (2004) Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations. [Online]. Available: http://www.nerc.com.
[12] P. Nedwick, A. F. Mistr Jr., and E. B. Croasdale, "Reactive management: A key to survival in the 1990s," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 1036–1043, May 1995.
[13] T. Wiedman, "Protective relaying action associated with widespread system disturbances," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.
[14] "Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy," UCTE, 2004.
[15] P. Gomes, N. Martins, P. de Mello, and X. V. Filho:, "Assuring system reliability in a competitive environment," in *Proc. CIGRE Meeting*, Paris, France, Aug. 1998, 38–104.
[16] J. J. Paserba, S. Noguchi, M. Shimomura, and C. W. Taylor, "Improvement in the performance and field verification of an advanced high side voltage control (HSVC)," in *Proc. IX Symp. Specialists in Electric Operational and Expansion Planning (IX SEPOPE)*, Rio de Janeiro, Brazil, May 23–27, 2004.
[17] P. Kundur, G. K. Morison, and A. Moshref, "Measures to improve power system security in the new competitive market environment," in *Proc. VIII Symp. Specialists in Electric Operational and Expansion Planning*, Curitiba, Brazil, May 2000.
[18] P. Kundur and G. K. Morison, "Techniques for emergency control of power systems and their implementation," in *IFAC/CIGRE Symp. Control of Power Systems and Power Plants*, Beijing, China, Aug. 1997.
[19] P. Donalek, "A description of discrete supplementary controls for stability," *IEEE Committee Report; Paper F 76-626-2, IEEE Trans. PAS*, vol. PAS-97, no. 01, pp. 149–165, Jan./Feb. 1978.
[20] P. Kundur and G. K. Morison, "On-line dynamic security assessment of power systems," in *Proc. VI Symp. Specialists in Electric Operational and Expansion Planning*, Salvador, Bahia, Brazil, May 1998.
[21] S. H. Horowitz and A. G. Phadke, "Boosting immunity to blackouts," *IEEE Power Energy Mag.*, pp. 47–53, Sep./Oct. 2003.
[22] H. You, V. Vittal, and X. Wang, "Slow coherency based islanding," *IEEE Trans. Power Syst.*, vol. 19, no. 1, pp. 483–491, Feb. 2004.
[23] H. You, V. Vittal, and Z. Yang, "Self-healing in power systems: An approach using islanding and rate of frequency decline based load shedding," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 174–181, Feb. 2003.
[24] C. Rehtanz, "Versicherungen gegen blackouts," *SEV/AES Bulletin, Switzerland*, no. 4, 2004.
[25] ——, "New technologies for network security enhancement," presented at the CIGRE Panel Session, CIGRE General Session, Paris, France, 2004.
[26] C. W. Taylor and R. E. Wilson, "BPA's wide-area stability and voltage control system (WACS): Overview and large-scale simulations," in *Proc. IX Symp. Specialists in Electric Operational and Expansion Planning (IX SEPOPE)*, Rio de Janeiro, Brazil, May 23–27, 2004.
[27] P. Pourbeik, R. J. Koessler, and B. Ray, "Addressing voltage stability related reliability challenges of San Francisco Bay area with a comprehensive reactive analysis," in *Proc. IEEE PES General Meeting*, Toronto, ON, Canada, Jul. 2003.
[28] E. John, A. Oskoui, and A. Petersson, "Using a STATCOM to retire urban generation," in *Proc. IEEE PES Power Systems Conf. and Expo.*, New York, Oct. 10–13, 2004.
[29] C. W. Taylor, "Improving grid behavior," *IEEE Spectrum*, pp. 40–45, Jun. 1999.
[30] N. Hatziargyriou and G. Strbac, "Microgrids: A possible future energy configuration?," in *IEA Seminar "Distributed Generation: Key Issues, Challenges and Roles"*, Paris, France, Mar. 1st, 2004.
[31] M. M. Adibi, *Power System Restoration: Methodologies and Implementation Strategies*. New York: IEEE Press, 2000.