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

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Abstract— On August 14th 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 23rd 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 28th. 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. A summary is given of the major conclusions drawn from the presentations, as well as general conclusions drawn by this Committee.

I. INTRODUCTION

The all day panel session on Major Grid Blackouts of 2003 in North America and Europe, was held on June 8th, 2004 at the IEEE Power Engineering Society General Meeting in Denver, Colorado [1 – 10][2]. Section II of this paper presents a summary of the causes of the three major blackouts. Section III presents a brief summary of the recommendations made by the panelists and through general discussion at the panel session. Section IV presents a 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?

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

The US-Canadian blackout of August 14th, 2003 affected approximately 50 million people in eight US states and two Canadian provinces, resulting in the interruption of approximately 63 GW of load. Based on the North American Electric Reliability Council (NERC) investigation [2,

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11], a combination of inadequate system understanding, inadequate situation awareness, lack of vegetation management and lack of diagnostic support from reliability organizations lead to the cascading outages that resulted in the blackout. 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 and real time contingency analysis software were 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 software starting at 14:14. This contributed to inadequate situational awareness at FE (until approximately 15:45).

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. 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. As the operator attempted to restore automatic voltage control the generator tripped. A modern excitation system automatically returns to voltage control when conditions permit.

At approximately 16:10, due to the cascading loss of major tie lines in Ohio and Michigan, the power transfer between the US 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.

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, 12]:

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 [12]. 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 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. 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 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 country wide blackout. This was the worst blackout in the history of the nation.

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

A. Data Management [7]:

There is a need for improvements in calibration of recording instruments, particularly in time synchronization, and establishing predefined data reporting standards and confidentiality agreements for data sharing.

B. Disturbance Monitoring [8]:

There is a need for refining the process for integration, analysis and reporting of wide-area measurement systems (WAMS), and allowing the free exchange of WAMS data to promote its development. This must also include the development and support of staff and resources.

C. International Perspective and Recommendations [3, 4, 5, 9, 10, 13]:

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 application of automatic controls such as automatic voltage regulators, and where applicable power system stabilizers, should be mandatory for generators. It is also of vital importance to enforce and constantly encourage training programs for system operators and their supporting staff. Voltage stability can often be a major concern, thus proper reactive power management, having under voltage load shedding schemes to protect against severe unplanned for disturbances and proper employment of shunt reactive compensation are key to ensuring system reliability.

IV. NEW AND EMERGING TECHNOLOGIES TO ASSIST IN POWER SYSTEM SECURITY

To maintain power system reliability and security at one hundred percent 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. Also, a wide range of new and emerging technologies could assist in significantly minimizing the occurrence and impact of widespread blackouts. Some such techniques and technologies are briefly described below.

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 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 [15, 16, 17].

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 [18]. 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 [19]. Other adaptive controls such as adaptive islanding [20] and automatic load shedding [21] 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 [22, 23]. Wide-area stability/voltage control may be used for generator or load tripping, or mechanically or power electronic switched reactive compensation devices. [24]. 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 [25, 26]. 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 and 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 [27]. Power plant controls to tightly regulate transmission side voltage have also been demonstrated and are available, which can further enhance voltage stability [10,14]. 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, VSCs 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, with VSCs, 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 [28].

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 and 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 three 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.
2. 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.
3. 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.

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