Chapter 4
Transmission Blackouts: Risk, Causes, and Mitigation

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Glossary

DOE	Department of Energy
EMS	Energy Management System
FACTS	Flexible AC Transmission System
FERC	Federal Energy Regulatory Commission
GPS	Global Positioning Satellite
ISO	Independent System Operator
NERC	North American Reliability Council
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
RAS	Remedial Action Scheme
TSO	Transmission System Operator
SCADA	Supervisory Control and Data Acquisition
SIPS	System Integrity Protection Scheme
UCTE	Union for the Coordination of Transmission of Electricity
WAMPAC	Wide Area Monitoring, Protection, and Control
WECC	Western Electricity Coordinating Council

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Definition of the Subject and Its Importance

Power system blackouts result in complete interruption of electricity supply to all consumers in a large area. While it may be possible to trace a blackout's beginning to a single incident (e.g., transmission line sagging into a tree), cascading outages are the result of multiple low-probability events occurring in unanticipated or unintended sequence. The likelihood of power system disturbances escalating into a large-scale cascading outage increases when the grid is already under stress.

Blackouts may look like bad luck, but they are result of how the grid is managed. Statistically, a sequence of low-probability contingencies with complex interactions causing a blackout may not happen often but will eventually take place unless measures are taken to prevent it. Presently, some of the grids around the world (e.g., parts of the North American grid) may be susceptible to blackouts as aging and insufficient grid infrastructure may not be adequate to accommodate grid changes, such as renewable generation resources and load growth. Deployment of "Smart Grid" monitoring, control, and protection devices, software tools, and telecommunication infrastructure helps better manage the grid, but does not replace investments in the infrastructure.

Although large-scale blackouts are very low-probability events, they carry immense costs for customers and society in general as well as for power companies. It is easy to misjudge the risks and costs of such extreme cases.

Although widespread outages cannot be completely prevented, their occurrence can be reduced, propagation (size) and consequences arrested, and restoration sped up. In last couple of decades, power systems around the world have been more stressed as the capacity reserves and system margins have been reduced resulting in more blackouts with huge costs to the society.

Introduction

Wide-area electrical blackouts have raised many questions about the specifics of such events and the vulnerability of interconnected power systems [1–4]. Power systems are complex interconnected machines with many components operating in harmony when the system is balanced. When a problem occurs in part of the system, the impact of the trouble may cause to the system losing its balance momentarily. In most cases, the system is immediately isolated and shortly after recovers with no further propagation observed outside of the immediate area.

Exchange of information stemming from the recent worldwide blackout findings and "smart grid" technology innovations shed new lights on the current conditions and needs of power systems. Examination of the root causes, the resulting effects on neighboring systems, and implementation of proven solutions to help prevent propagation of such large-scale events should help in designing and operating reliable "smart grid" and power delivery infrastructures for today and in the future.

Power system professionals can take in consideration the costly lessons of the past, maintain a library of historical lessons about "What and Why it Happened" for the generations to come, and act as catalysts to achieve desired level of power system reliability.

The high cost and the need for extensive mitigation strategies against grid congestions, combined with this type of probabilistic assessments, have led into risk management not focusing on appropriate, cost-effective mitigation actions. From a broader prospective, a misconception may be formed about the grid reliability or its exposure to large-scale outages every so often. It is easy to misjudge the risk of such extreme cases. (Risk is the product of the cost and associated probability, and both factors are very hard to assess accurately.) The high costs of extensive mitigation strategies (e.g., building new transmission lines), combined with inaccurate probabilistic assessments ("blackouts will not happen in my system"), have led to inadequate risk management practices, including not focusing on cost-effective prevention and mitigation initiatives. Such initiatives can provide value through avoidance of huge blackout costs. The following stakeholders benefit from outage/blackout avoidance:

- The society/ratepayers. For example, society costs for August 14, 2003 blackout in the USA and Canada and for August 2006 WECC blackout were estimated at $7B and $1B, respectively.
- The electric utilities, ISOs, generation producers, etc. Costs of service restoration, undelivered energy, cost of litigation, and the negative impact on stock price.

Understanding the complexities of the interconnected power grid, need for proper planning, good maintenance, and sound operating practices are the key to deliver electric power to modern day necessities and prevent the problems of tomorrow's grids. This article offers practical insight on risks and leading causes of widespread blackouts and how best to prevent them to achieve higher levels of grid reliability.

Grid Development History

In the 1930s, electrical power was delivered to consumers around the world by individual, not connected electrical systems. Regional systems have been created next to make power systems more robust and delivery more reliable. The original function of the interconnected systems was to form the backbone for the security of supply and to reach its required high reliability level at reasonable costs. In the 1950s, the power system professionals foresaw the importance of further improving delivery of reliable electricity to consumers. The grid systems have been developed to assure mutual assistance between transmission system participants and/or national subsystems including common use of reserve capacities to optimize the use of energy resources by allowing exchanges between the systems.

Thus, a strategy of interconnecting neighboring systems to improve reliability and security margins became a reality around the world. Coordinated rules for the mutual support of interconnected systems were defined and adopted by the power pool members between power systems, including interconnections among countries (e.g., UCTE in Europe). Since the late 1970s, the electrical transnational infrastructures were exploited more and more for energy exchanges that took advantage of the different production costs of electricity in the various nations or interconnected grids in order to deliver lower cost energy and achieve maximum profits. However, the bulk power system was not originally engineered to transfer large amounts of power between neighboring systems over long ranges but to enable neighboring utilities to support each other during stressed conditions.

In recent years, deregulated energy concepts have created additional burden on the system for using the same conductor for additional capacity increasing already high transfers as new generation sources (including renewable energy) are brought on-line to meet the demand. The high level of power exchanges in today's energy market is technically being provided outside of the scope of the original system design. The higher demand, coupled by low level investments in technology and infrastructure upgrades and capacity increase, has led the Control Area operators to run the system close to the edge, as close to the limits as permitted by the reliability criteria and, sometimes, beyond the limits. At the same time, our increased respect and awareness for the environment and the "Not in My Backyard" sentiments have made it difficult to site transmission lines or major local generation sources, especially in the more densely populated areas, where load is heavy. These difficulties make the system expansions expensive and difficult, and offer new challenges to deliver reliable power.

Recently, major investments have been made worldwide in "smart grid" technologies, e.g., US DOE investment grants. Major motivation for Transmission "smart grid" is in preventing blackouts using Wide Area Monitoring Protection and Control (WAMPAC) technologies, such as synchronized measurements using GPS signals.

There are still isolated power systems around the world (e.g., island networks). Unlike interconnected grids, those power systems do not have flexibility to get help from the neighboring systems to optimally balance generation and load, both during normal and stressed conditions. Those systems are more vulnerable to generation and transmission system outage and require long-term, coordinated planning and investments in the complete electrical grid infrastructure to achieve reliable and cost-effective grid operation and maintenance.

Challenges in Taming the Grid from Wide-Area Blackouts

Evolutions in technology continue to improve all aspects of our lives from precision surgical equipment for use in highly critical operations, to automatic banking anytime of the day, electric rail systems to reduce emissions, and to our home

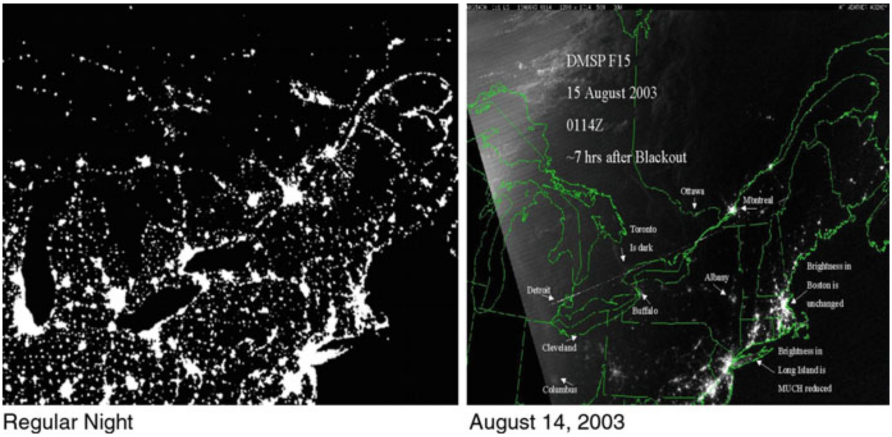

Fig. 4.1 Effects of August 14, 2003 blackout in North America

appliances. Many of the technological innovations have been achieved in recent quarter century and have readily found their way in our daily lives. The modern day amenities and our respect for the environment have also increased our dependency on energy, hence, our expectations for uninterrupted reliable power. However, the demand for availability of power for many of these modern day equipment has not been systematically and uniformly considered. Modern technology is the catalyst driving power delivery demanding grid reliability, and the marked increased dependency on availability has raised the bar on human expectation.

Some of the electrical power systems that experienced blackout in last decade (e.g., North America, Europe) are among the most reliable systems worldwide. However, they are subject to a host of challenges – aging infrastructures, renewable and distributed energy integration, transmission and distribution grid expansion to meet the growing load demand and transfer renewable energy to load centers, etc. Figure 4.1 shows impact of the 2003 blackout on supplying power to the consumers (before and after the blackout).

After some major blackouts worldwide in the last 2 decades, utilities have hardened their electrical systems, and regulatory organizations (e.g., NERC and FERC and state regulators in the USA) have focused on defining and enforcing reliability standards. This has resulted in better planned, operated, and maintained grid. However, one of the challenges facing the electric industry today is the balance between reliability, economics, environmental, and other public purpose objectives to optimize transmission and distribution resources to meet the demand. Resources and transmission adequacy are necessary components of a reliable and economic supply. Though the reliability and market economics are driven by different policies and incentives, they cannot be separated when the objective is reliability and availability. Today, grid planning in the regional and interregional environment faces an extremely difficult task given the challenge to achieve resource adequacy in today's restructured industry, where market economics, local concerns, and renewable energy resources often derive the decision for generation facility siting remote from major load centers. Equally difficult is planning for an adequate transmission system when the location of future generation facilities is uncertain and the lead time for transmission construction is very long (just the permitting process may take several years).

It is more important than ever to find ways to project transmission and distribution growth, solutions to deploy, and criteria to be applied to guide prudent investment decision. Some of the key areas to address are the following:

- Integration of renewable energy – As renewable resources (e.g., wind and solar) are located far from the load centers, additional stress was put on the system, causing higher vulnerability to outages.
- Price for reliability – Costs and risks transmission owners and customers are willing to assume. The power industry is accustomed to optimize investments and evaluate return on investments based primarily on financial aspects of trading energy and serving load within certain reliability criteria. This is often done without considering financial aspects of unavailable energy (undue service interruptions) due to low reliability and slow restoration that incurs significant costs to the society. This is an incomplete financial model that results in suboptimal investment strategies.
- Large regional geographic areas should be included in the scope of transmission planning and decision-making. However, when assets need to be built, it is not easy to identify true beneficiaries and how costs are to be shared.
- Quick restoration – As it may not be possible to completely avoid outages, it is required with today's technology to reduce power restoration.

Electricity is the key resource for our society; however, strategic planning (regional and national) requires additional priority to improve system reliability.

History and Examples

Within the last decade, the number of wide-area outages has rapidly increased (blackouts in north-east USA and Canada, western USA, Brazil, Italy, Sweden, Denmark, England, India, Malaysia, Australia, New Zealand, Greece, etc.) affecting over 300 million customers worldwide. As the likelihood of low-probability events escalating into a cascading outage increases when the grid is already under stress due to preexisting conditions, one can conclude that power grids are more prone to disturbances than ever.

History has showed that both unscheduled and scheduled (regular maintenance) outages have affected power system's balanced operation hence signifying the grid complexity during managed conditions [1, 2, 5–7]. In the case of the August 1996 North America disturbance that affected 12 million people [5], a series of equipment were being removed for maintenance in parts of the Western grid when the weather was moderate, yet these pieces of equipment were needed to support transfers in other parts of the Western grid, which was experiencing extremely high temperatures.

Analysis of the 2003 incident in the north-eastern part of the USA [6], which affected 50 million people, revealed that a series of cascading events over the course of several hours, rather than a single instantaneous problem, initiated the major disturbance phenomenon that toppled the large part of the US Eastern Interconnection. The blackout itself was preceded by scheduled generation outages and line tripping caused by overgrown trees in the right-of-way. It was accompanied by failures of EMS/SCADA alarm systems, which prevented operators from diagnosing problems. The initial line disconnection caused another 345 kV line to overload and sag into a tree, resulting in remaining 345 kV lines to disconnect. Underlying 135 kV lines overloaded and disconnected, followed by tripping of generating units, causing a part of the system to go black. A lack of communication and coordination between utilities and ISOs involved exacerbated the problem. The grid was restored in 1–2 days (depending on the area affected and ability to get generators back on line).

The September 2003 disturbance in the connected European grid affected 57 million people. Several 220–400 kV lines were out of service for maintenance reasons prior to the event occurrence. Italian grid was importing 6 GW from the rest of the grid. One of the 380 kV lines disconnected due a tree contact. The parallel line overloaded, and although the import was reduced, it was not enough to prevent sagging into a tree and disconnecting. Other lines to Italy overloaded and tripped, resulting in isolating Italian grid 12 s after the loss of the second line. During those 12 s, low voltage in northern Italy caused generators to disconnect. Other countries tripped generation (app. 6.7 GW). In summary, 2.5 min after islanding, Italy goes black separated from the rest of the grid. However, unlike the blackout in the USA, it took only 5–9 h to restore the power to major cities. Main reasons are for faster restoration was type of generation that was able to get back on line faster and accompanying restoration processes (e.g., so-called black-start capabilities allowing fast generation reconnection).

The most severe disturbance in the history of UCTE considering number of Transmission System Operators (TSOs) involved happened in October 2006 [7] when system separated in three islands. Following were key reasons for the disturbance:

- N-1 criterion (planning criteria so that a single equipment outage does not create a system disturbance) was not fulfilled as wind generation was not adequately predicted. Large wind storms increased production in northern Germany.
- Inappropriate inter-TSO coordination and training. The time of the planned line outage was changed, and new conditions were not checked.
- Uncoordinated protection settings on both sides of the critical line.
- Uncoordinated operation of wind generators.
- Inadequate coordination of restoration.

All the above blackouts included combination of phenomena such as line overloads, voltage and angular instability, and system separation. Those blackouts have served as catalysts in propelling the power industry toward analyzing blackouts and finding solutions to prevent such occurrences. The 1994–1996 blackouts in the western part of North America resulted in formation of investigating teams which ultimately made a combined list of 130 conclusions and 54 recommendations [7]. The August 14, 2003 investigating teams identified 60 recommendations (14 by North American Reliability Council, or NERC, and 46 by the US Canadian Task Force) [6]. The Union for the Coordination of Transmission of Electricity (UCTE) identified 14 observations for the September 28, 2003 outage, very similar to those identified for the outages in North America that happened just a month before. Although major improvements have been accomplished after the blackouts in corresponding grids, the similarities in findings among those blackouts prove that if recommendations had been used among grids, the impacts of the outages could have been minimized [4].

By some accounts [8]:

- These kinds of outages are consistent with historical statistics, and they will continue to happen. Some may compare blackouts to events such as long-term weather forecasting (hurricane and mudslides) or to natural disasters such as earthquakes as being difficult to predict and/or to prevent.
- The more immediate problem may be the industry's investment of less than 0.5% in R&D, one of the lowest rates for any industrial sector.
- A power system is composed of hundreds of thousands of pieces of equipment from bulk autotransformers, high-voltage transmission systems, to a light bulb. It has been suggested that one could not get a computer big enough to model a complex system as, for example, the Eastern Interconnection and perform the planning studies.
- Large blackouts occur because the grid isn't forcefully engineered to prevent them. Purposely weakening the grid can reduce large blackouts but would increase the frequency of smaller ones.

Chifong Thomas, formerly transmission planning engineer from Pacific Gas and Electric Co. points out that if large blackouts occur anyways, as they are hard to predict as earthquakes, then nothing anyone could do would make any difference. This contradicts the premise that industry underinvestment in R&D is the immediate problem. If the first premise is true, the second one is irrelevant. She also points out that if the grid planning is done comprehensively and correctly, then operators with proper training should have time to respond to contingencies and/or to limit the impacts of the contingency.

Dr. Mayer Sasson, principal advisor of Electric Markets Policy Group at Consolidated Edison Co. of New York, highlights the vulnerability of the interconnected grid by pointing out that it may take only one member of a control area to be operating outside of the reliability limits for any reason, including unintentionally, to cause a cascading outage that can quickly propagate to neighboring interconnected system control areas. This underscores the criticality of complying with mandatory reliability rules.

Dr. Bogdan Kasztenny, power system protection and control application manager at Schweitzer Engineering Laboratories, raises the important issue of human factor involvement in the last few critical hours before any major event. "Even in a poorly designed and under-invested system, operators could sometimes salvage an event that seems to be disastrous, or collapse an otherwise quite secure situation in a strong and reliable system. It is not so with earthquakes. Power systems are man-made creations run by humans. Operational procedures, availability and accuracy of real-time information, adequate training including dry runs on simulators are technical means that improve response of the operators."

Kasztenny emphasizes that the power system is a complex generating, transmitting, and distributing system for a medium that cannot be stored, or buffered, in the reality of very limited redundancy. This makes it quite different from the banking, phone, or similar systems. Other systems are subject to brownouts. However, the power system must balance the medium under physical constraints and is therefore subject to collapse if the constraints are violated.

Pre-outage Conditions and Risks for Blackouts

The grid is a tremendously complex system, and the interconnections that allow us to benefit from higher reliability and lower costs also cause the domino failures experienced in many parts of the world in recent years. Although there is a tendency to point at one or two significant events as the main reasons for triggering cascading outages, major blackouts are typically caused by a sequence of low-probability multiple contingencies with complex interactions. The three "Ts" – Trees, Tools, and Training – have been identified as the leading focus areas to prevent widespread outages not caused by natural events. However, disturbances have occurred following extremely low-probability successive unscheduled equipment outages beyond planning criteria. There have also been cases of system disturbances caused by scheduled equipment outages when the electrical system has not been adjusted, for continued safe operation, prior to the equipment being removed. Low-probability sequential outages are also not anticipated by system operators, thus rendering the power system more susceptible to wide-area blackouts. As the chain of events at various locations in the interconnected grid unfolds, operators cannot act quickly enough to mitigate the fast developing disturbances.

Power systems are engineered to allow for reliable power delivery in the absence of one, two, or more major pieces of equipment such as lines, transformers, or bulk generation, commonly referred to as contingency conditions. For example, after the 2003 blackout in North America, North American Electric Reliability Council (NERC) set forth the reliability standards and performance requirements that are enforced by audits. However, the complexity of the grid operation makes it difficult to study the permutation of contingency conditions that would lead to perfect reliability at reasonable cost. Accurate sequence of events is difficult to predict, as there is practically an infinite number of operating contingencies. With system changes, e.g., independent power producers selling power to remote regions, load growth, new equipment installations that cause significant changes in power flow to name a few, these contingencies may significantly differ from the expectations of the original system planners and engineers.

The likelihood of power system disturbances escalating into a large-scale blackouts increases when the grid is already under stress due to preconditions. Those preconditions are summarized as follows:

- Congested grid with tight operating margins
  - Not building lines or generation as fast as required, exacerbated by difficulty in identifying business models to recover costs, and a cumbersome permitting process
  - Not well-planned wholesale merchant transactions with scheduled transactions not changed to allow for transmission relief when required
- System stress caused by intermittent renewable energy and/or suboptimal operating practices
- Insufficient reactive support where and when required to maintain required voltage levels
  - Adequate dynamic reactive power is required close to the load as reactive power cannot be transferred over long distances
- Uncoordinated planning between transmission and generation
  - Inadequate system reserve, such as generation spinning reserve
- Inadequate planning/operation studies
  - No routine use of an effective contingency analysis tool
  - Uncoordinated interregional transmission planning
- Aging infrastructure, prone to failures, accompanied by insufficient level of investment in maintaining the grid
  - It is more and more difficult to isolate and remove equipment for maintenance
- Both scheduled and uncoordinated maintenance
- Lack of system and component knowledge (e.g., system operator not aware of line loading margins)
- Inadequate right-of-way maintenance or environmental policies versus right-of-way vegetation management
- Weather (high temperatures; wind, thunderstorm, fog, etc.)
- Regulatory uncertainty
- Inadequate Automatic Warning, Protection, and Control Systems

In general, combination of various factors makes power systems more susceptible to disturbances.

Symptoms of Blackouts

It is the cascading events that cause disturbances to propagate and turn into blackouts. System is stressed and as system and equipment faults occur, the chain of events starts. For example, some generators and/or lines are out for maintenance, line trips due to a fault. Other lines get overloaded, and another line gets in contact with a tree and trips. There is a hidden failure in the protection system (e.g., outdated settings or HW failures) that causes another line or generator to trip. At that stage, power system is faced with overloaded equipment, voltage instability, transient instability, and/or small signal instability. If fast actions (e.g., load shedding, system separation) are not taken, system cascades into a blackout.

Evaluation of disturbances shows that protection systems have been involved in 70% of the blackout events [9]. For example, distance relays trip on overload and/or low-voltage sensitive or ground overcurrent relays trip on high unbalance during high load. Inadequate or faulty alarm and monitoring equipment, communications, and real-time information processing can further exacerbate disturbances in the system. Either information is not available or operators are flooded with alarms, so they cannot make proper decisions fast.

Human error and slow operator response are major contributing factors for cascading outages. As a disturbance develops, operators in various regions are faced with the questions "is the best course of actions to sacrifice own load, cut interties, or get support from neighbors?," "should we help or should we separate?." Important aspect in designing connected power systems is that individual systems should not allow cascading outages to spread throughout the system.

There are a number of other contributing factors that allow a blackout to spread, including lack of coordinated response among control areas. If each region focuses primarily on its own transmission system, the total connected system may not be reliable. As it is very difficult for operators to decide on best actions during a fast developing disturbance, it is desirable to take automated actions before system separates or to separate it in a controllable manner.

Generally, disturbance propagation involves a combination of several phenomena:

- Equipment tripping due to faults or overloads (e.g., transmission lines and transformers). These events may cause other equipment to get overloaded, creating a cascading event contributing further to system-wide outages.
- Power system islanding (frequency instability) when power system separates. Islands are formed, with an imbalance between generation and load, causing the frequency to deviate from the nominal value, leading to additional equipment tripping.
- Loss of synchronous operation among generators (angular or out-of-step instability) and small signal instability that may cause self-exciting inter-area oscillations if not damped.

Table 4.1 Types of wide-area events for different transmission systems

System config.	Densely meshed power system with dispersed generation and load		Lightly meshed transmission systems with localized generation and load	
Events	Located in a large interconnection	Not interconnected or by far the largest partner	Located in a large interconnection	Not interconnected or by far the largest partner
Overloads	**	**	*	*
Frequency instability	*	**	*	**
Voltage instability	*	*	**	**
Transient angle instability	*	*	**	**
Small signal stability	*	*	*	*

*Phenomena did not affect a particular grid configuration in the past, but have affected modern grids
**Major phenomena in a particular grid configuration

- Voltage instability/collapse problems that usually occur when the power transfer is increased and voltage support is inadequate because local resources have been displaced by remote resources without the proper installation of needed transmission lines or voltage support devices in the "right" locations.

Table 4.1 shows the types of wide-area disturbances likely to occur in two different types of interconnected power grids, namely, meshed network versus an interconnected transmission system of narrow corridors consisting of extensive generation tied to the interconnection [10]. One star indicates that those phenomena did not affect a particular grid configuration in the past, but have affected modern grids. Two stars indicate major phenomena in a particular grid configuration.

The characteristics of the power system influencing the types of mitigation methods have been described in a variety of literature [1–4, 9–13]. The relative time of action for different type of events, from normal to extreme, varies depending on the type and speed of the disturbance and the need for coordination. Example of the time line for different type of events is shown in Fig. 4.2.

Deployment of a well-coordinated overall defense plan to prevent blackouts requires implementation and coordination of various schemes and actions, spanning different time periods. When events can be controlled to result in gradual shutdown of the available resources rather than permitting them to cascade, their impact could be minimized. A practical approach to identifying stressed system conditions, which are symptomatic of cascading, is feasible. This can be done by defining and modeling the power system parameters considered for reliable operation such as voltage, frequency, or phase angle at critical locations. Such findings can then be implemented through investments in Hardware equipment and Software tools that help manage the grid more effectively.

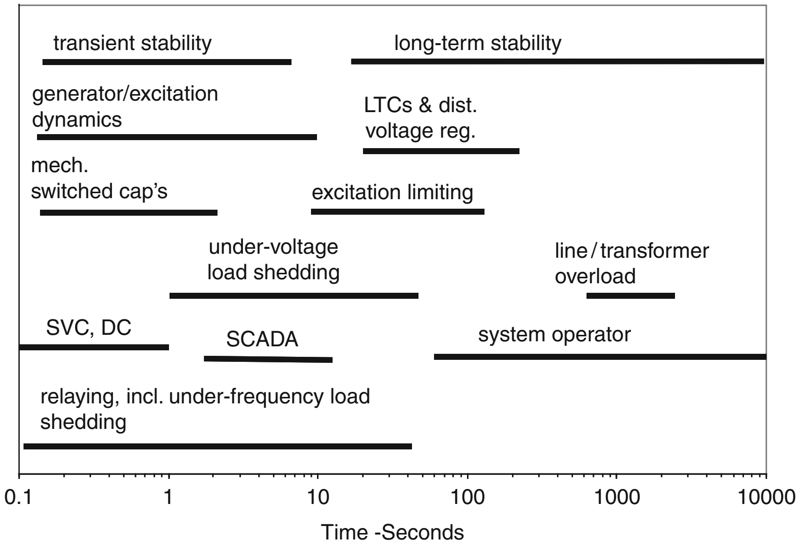

Fig. 4.2 Some time frame factors of power system dynamics

Power System Modeling and Analysis

Electrical grids have been characterized as the most widespread interconnected, complex, dynamic systems made by humans. A power system carries tremendous amount of electricity that all depend on. Although blackouts are difficult to predict and prevent, the notion that it is not possible to simulate the grid behavior, to identify and address most vulnerabilities, is not accurate.

Carson Taylor, power system simulation expert (formerly with Bonneville Power Administration), confirms that today's technology allows for detailed modeling of complex power systems. Taylor emphasizes that the Eastern Interconnection has been simulated in great detail with 40,000+ bus models. Simulations with 100,000+ models are feasible. Feasibility increases with IT advancements. Computation is not a large problem. Computation is scalable by parallel computation on multiple servers; cases can be farmed out to the multiple servers. Simultaneous processing method is used for energy management system dynamic security assessment.

Professor Göran Andersson, Eidgenössische Technische Hochschule (ETH) University in Zurich and a noted expert in power system dynamics, concurs with Taylor and brings up an important issue that the challenge is not technical, i.e., modeling or computer capacity related; rather it is the data management and proper interpretation. Professor Andersson also underlines that the "Statistical methods can give some information and insight concerning the sizes and frequencies of blackouts, which is of value. However, the problem is the calibration of the frequency scale, since this requires a detailed modeling of the interactions.

The statistical insights, however, do not provide to any large extent the guidance to avoid blackouts to the power system professionals operating the systems. In terms of modeling, the details of the system and the interactions between different components and subsystems are indispensable."

Both Andersson and Taylor emphasize that best practice is to continually improve and update models and compare simulations with real power system response. This is not unique for power systems and is continuously being done in the industry and academia. In addition, much progress has been made over the years, and even if predictions from simulations are problematic, efforts to model, simulate, and validate performance provide invaluable insight for a reliable power system operation.

In conclusion, the power grid can be modeled and studied; however, as there is an infinite number of contingencies that can occur and the current state is not precisely known, it is not possible to exactly predict disturbance propagation far in the future. However, innovations in power system tools from planning, to monitoring, to operation are strategies that would help in meeting the challenges of the twenty-first century expectations in reliable power delivery.

How Disturbances Turn into Blackouts

It has been demonstrated time and again that wide-area blackouts are caused by operation of the interconnected power system outside of the operating limits or for operating conditions that have not been thoroughly studied. As described by Vahid Madani, principal engineer at PG&E, one of the ways to understand the challenges of power delivery is to liken it to driving the highways via motor vehicle. As motor vehicle operators, most of us have experienced a wide variety of unplanned difficulties and challenges slowing down our travels. In many ways, widespread outages have similar characteristics as a highway traffic gridlock. Some of the key aspects of traffic jams include the following:

- Not enough lanes to accommodate the growing demand.
- As one or two lanes are closed, the traffic flow is significantly impacted, and in the most severe case, it causes a complete highway shutdown. A circumstance out of control of those not involved with the accident, yet they are stuck (blackout).
- A properly designed system would include major alternate freeways that are easily accessed through proper detours to minimize impact from the gridlocks.
- Repair of the old highways may not be enough to solve traffic congestion. At times prudent investments in building new traffic lanes, or completely new thruways, and innovative traffic control systems are needed.

Dr. Daniel Karlsson, system analysis and protection expert from Sweden, also compares the expansion of highway traffic with an expansion of the power grid as both have grown from minor systems to extremely important infrastructures in the same time period and both continue to grow. However, he points out that the public accepts a much higher degree of failures (e.g., people seriously injured or worse) due to automobile traffic than they accept a widespread power outage, demonstrating the important role of electricity in our daily lives and hence the criticality of reliable power delivery.

> Karlsson brings up a historical perspective to explain how the large interconnected power systems of today have been formed due to constant demands on capacity, economy, and reliability. He points out that initial power systems were small grids with low capacity and low reliability. Extensions emerged as dictated by capacity needs. To improve reliability of the individual systems by allowing support from the neighbors, these systems were interconnected. New phenomena appeared, such as transient instability, resulting in studies and actions to counteract them. Complex powerful power systems introduced new transmission capacity problems and actions to counteract them (series capacitors inserted in the transmission line, shunt capacitors and reactors, automatic tap changers to control transformer voltage, etc.). This consequently brought new phenomena like sub-synchronous resonance and voltage instability and, again, a need for new studies and equipment, such as Flexible AC Transmission Systems (FACTS), High Voltage DC (HVDC) links. Dr. Karlsson emphasizes that the complexity of the present power system, and factors such as environmental and rights of way, governmental, cost-to-benefit evaluation for large scale investments will derive us to maximize the use of current assets without truly addressing the rising demand for new infrastructure. This trend will continue to challenge the industry with new technology and actions: superconductivity, energy storage, micro-grid, etc.

There is also a strong relation between system size and reliability. In the ever growing demand to be supported by the power system, our industry tends to push the limits challenging the reliability with a question, "where is the edge?" This is particularly true in many places such as North America, where the expansion efforts are not growing as much, or as rapidly as, the grid is being utilized.

It is noted that weakening or splitting the grid on purpose during normal operation is not a sound alternative, as this strategy would make a full circle for the grid. For example, by operating the power grid in separate islands, one could easily weaken the power system. That would effectively mean coming back to the original design of the small grid with low capacity. Separating the grid into islands would also impact deregulation, e.g., each DG would be selling power to its own neighborhood. The small utility will soon need occasional support for reserve margin, voltage, and reactive margins from neighboring systems, hence, back to the interconnected grid. The solution is not in separating the grid into islands, rather to resolve transmission problems to mitigate potential for widespread cascading outages.

Chifong Thomas dismisses the argument that large blackouts occur because planning engineers spend too much time preventing small blackouts. She argues that this theory ignores the fundamental fact that large blackouts start out as small problems that do not by themselves necessarily lead to blackouts. They lead to blackouts when small problems are not corrected in time.

Professor Vijay Vittal, Iowa State University, corroborates that the impact of such severe system failures could be mitigated by several approaches such as use of corrective controls or performing more effective analysis closer to real time.

The effective way to minimize disturbance propagation is to truly understand the common causes and design the appropriate solutions. The system needs to be addressed as a whole, implementing various planning, operations, maintenance, and regulatory measures in a coordinated way.

A possibility to prevent propagation of the disturbance throughout interconnected grid, but not weaken the grid during normal operation, is to design the interconnected power system to allow for intentional separation into stable islands or interrupt small amounts of load only when the system experiences major disturbances. As operators may not be able to act fast enough to take into account all data related to the on-line state of the system, separation actions should be done automatically. System Integrity Protection Schemes (SIPS) are wide-area automatic schemes that are designed to detect abnormal system conditions and initiate pre-planned automatic and corrective actions based on system studies [10–13]. They are also referred to as Special Protection Schemes (SPS), or Remedial Action Schemes (RAS). They detect abnormal wide-area system conditions and trigger automatic actions to restore acceptable system performance. The initiating factor in implementing significant number of SIPS in the western part of the USA (WECC) has been to better protect the system against multiple contingencies, particularly after the 1994 and 1996 blackouts [7]. Designing the grid with appropriate measures for voltage control and advance warning systems such as wide-area protection and control would allow for both strong interconnected grids during normal operation (to make system more reliable and secure) and creation of predetermined islands only when necessary.

In conclusion, instead of weakening the grid, power industry needs to address deregulation as one important aspect in understanding the underlying causes of system-wide outages. The bulk power system was often not originally designed to transfer large amounts of power between neighboring systems. Individual power systems were interconnected to improve electrical network reliability by enabling neighboring utilities to support each other during stressed conditions. In recent years, deregulation has imposed additional requirements of high transfers from new generation sources to the load areas. At the same time, public pressures and the “Not in My Backyard” sentiment make it difficult to site transmission lines or major local generation sources, especially in the more densely populated heavy load areas, making the system expansion very expensive and difficult. In addition, recent disturbances have, more and more, been accompanied by voltage stability problems.

In summary, following are the main reasons for disturbances to turn into blackouts:

- Inability to prevent sequential tripping due to overloads, power swings, and voltage fluctuations
- Inadequate or faulty EMS/SCADA system (incl. alarm burst) – need for reliable alarm filtering, proper visualization, and analysis tools
- Protection miss-operation or unnecessary actions
  - Incorrect settings, e.g., impedance-based protective devices tripping on overloads (NERC developed regulations after the 2003 blackout to address it)

  – Hidden failures: uncovered application design flows or HW failures
  – Inadequate design, e.g., application of impedance-based protective devices without the out-of-step blocking

- Inability of operators to prevent further propagation of the fast-developing disturbance
- Lack of coordinated response during developing disturbances, e.g., joint procedures between ISOs to deal with the problem quickly and effectively
- Generators tripping too early – generator tripping to be coordinated with the rest of the system

Blackout Prevention

The alarming increase in the number of major blackouts requires exploring new frontiers in deployment of well-defined and coordinated overall plans (planning, operations, and maintenance). As analysis of recent disturbances reveals some common threads among them, the conclusion is that propagation can be arrested and impact of disturbances reduced if knowledge gained is properly utilized [1–4].

The best way to minimize wide-area power system disturbance is to understand the leading causes. Study of blackout history in the past decade shows that in each case the reliability standards have been violated in some form or fashion demonstrating the priority for more stringent compliance enforcement of the standards, necessity to invest wisely in new transmission facilities that expand the reliability parameters of the grid in the "right" areas, new grid monitoring technologies, and especially the tools that help us make it simpler to manage the day-to-day operation.

Electric reliability and efficiency are affected by four segments of the electricity value chain: generation, transmission, distribution, and end use. Satisfactory system performance requires investments in all these segments of the system. Increasing supply without improving transmission and distribution infrastructure in the right locations, for example, may actually lead to more serious reliability issues.

The retirement and replacement of transmission equipment at the end of its useful life will be another important remedy for increasing failure rates and potential outages in the future. Aside from the aging infrastructure concerns, the transmission grid must be upgraded and expanded to continue to meet the growing demands. For example, high-voltage power electronic devices allow more precise and rapid switching to improve system control and to help increase the level of power transfer that can be accommodated by the existing grid. Distributed energy technologies, if properly applied, could also play a role in relieving power flow demands on the transmission networks. In conclusion, while the new investments shall certainly include some new transmission lines, it will also encompass power delivery technologies such as series capacitors, single-phase operation of transmission lines, FACTS, HVDC links, energy storage, superconducting materials, and micro-grids.

The legislative and governmental commitments to build infrastructure, compliance with reliability requirements, and state, regional, and interregional plans are required to achieve the sustainable grid. Measure such as computerized control and data acquisition, phase-shifting transformers, coordination mechanisms, and electronic data exchange between operators are also some alternatives that improve the capability of the existing infrastructure and allow for a more robust power exchange.

Furthermore, reliable power system performance requires a balance of many critical components such as adequate reserve real and reactive power margins, reliable real-time telemetry and status monitoring, real-time state estimation, properly set, maintained, coordinated, and tuned protection and control systems, etc. Academic, industry, and governmental initiatives are required to set and enforce the standards for voltage control and reactive power practice, to improve system modeling and validation process, to enhance operator-training curriculum, and to assure that operators are assigned responsibility to take actions to prevent disturbance propagation.

In terms of modeling, quantitative analysis is needed to validate models of generators, turbines, and the associated controls to match actual system oscillations and damping. Likewise, dynamic loading or stability impact on protection devices (designed to operate for faulted conditions, e.g., tree contact) should be considered, and routine protection coordination studies using accurate model should be regularly performed. There are also concerns associated with protection and control application and settings when short-term market conditions for power transfers stress the equipment resulting in a risk of equipment outage.

Tools that improve real-time system monitoring, evaluation, visibility, security, congestion tracking, control, visualization, and information sharing about grid conditions over a wide region will allow operators to manage the grid more reliably on a day-to-day basis as well as in emergencies. Poorly recognized dynamic constraints can unnecessarily narrow operating limits and endanger reliability. Real-time security analysis tools are becoming increasingly critical for daily operation to visualize critical stability boundaries and to determine stability operating limits based on actual conditions.

Finally, the recent large-scale generation trips and remedial action responses have provided some very good benchmarks for combined small and large-scale analysis. Reexamination of traditional planning, operating, system design, protection applications, and device settings will help improve system response to slow or limit the spread of cascading outages. The frequency and varying impact levels of worldwide blackouts have provided the power industry with opportunities and supporting information to:

- Study the complex power system phenomenon to minimize propagation for future system-wide events using accurate and user friendly tools
- Validate the system studies against actual power system performance and governor modeling data

- Environmental and political factors limiting new addition of generation and transmission capabilities. Highlight the needed support for regulatory measures to ease wise grid expansions, grid reinforcements, and well-established and measured reliability enforcement process
- Operating capacity reserves and margins for transmission flows must remain available to allow system adjustments during unintended multiple contingency conditions. Enforce reliability requirements, for example, Planning Standards for Normal and Emergency Conditions
- Visit existing operating practices and real-time data exchange policies among control areas
- Make use of enhance maintenance practices and asset management tools
- Timely deploy Special Integrity Protection Schemes (SIPSs) to prevent spreading of the disturbance

Furthermore, protection systems are usually involved in major wide-area disturbances, sometimes preventing further propagation, and sometimes contributing to the spread of the disturbances [14]. A very important lesson is that the design and operation of conventional protection and control schemes have to be scrutinized assuming stressed conditions. Improvements to existing protection systems can help prevent cascading and minimize the impact and number of wide-area disturbances. In general, a protection system should operate only for its designed conditions. Preventing further disturbance propagation should be achieved by designing and setting protection, and control schemes do not miss-operate during major disturbance conditions. However, some experiences include relay operations that prevented further cascading by tripping on system conditions for which they were not designed.

Some key opportunities for improvement include coordinated adaptive protection and control systems and wide-area monitoring with advance warning systems, as elements of WAMPAC. The advance technology today promotes the concept of the "smart grid" – an integrated, electronically controlled power system that will offer unprecedented flexibility and functionality, and improve system reliability. The concept of the smart power delivery system includes automated capabilities to recognize problems, find solutions, and optimize the performance of the system.

In summary, corrective and preventive actions to avoid wide-area blackouts are the following:

- Provide operator with:
  - Tools to measure, monitor, assess, and predict both system performance and the performance of market participants
  - Training, incl. coordinated approach among control areas and use of dispatch training simulators
- Improve monitoring and diagnostics and control center performance
  - Availability of critical functions needs to be 99.99%
  - Assure adequate exchange of information between neighboring control centers

  - Secure real-time operating limits on a daily basis
  - Shared and consistent rating information required

- Use dynamic line ratings ambient temperature, wind, pre-contingency loading, etc., to better understand what the actual system margins are
- Better utilize available and standby generation in the area; implement black-start capabilities
- Improved maintenance and condition assessment of aging infrastructure
- Improve vegetation management
- Accurate generator, dynamic load, and reactive support device models, including renewable generation models
- Advanced algorithms and programs to assist the operator, such as "faster than real-time simulations"
- Protection coordination studies across regions and in coordination with equipment control and protection

  - Study and review protection designs on a regular basis, as system conditions change
  - Assure planned relay operation (e.g., distance relays not to trip on out-of-step and overload; ground overcurrent relays not to trip on high unbalance during high load, coordinated zone 3 operation, etc.)
  - Avoid hidden failures by adequate testing of not only individual relays but also overall relay applications
  - Increase the security of protection design in the areas vulnerable to blackouts

- Deploy Wide Area Monitoring, Protection, and Control (WAMPAC) systems to improve grid visibility and initiate corresponding actions

In conclusion, it is important to take a balanced approach to fixing the system as a whole by implementing various planning, operations, and maintenance measures and weighing the costs, performance impacts, and risks associated with each measure. One needs to evaluate how to operate and maintain the power system for the years to come to meet defined reliability objectives. There is no silver bullet solution to preventing blackouts, but there are general measures than can and should be taken to minimize impact of wide-area disturbances.

Each entity needs to focus on further process improvement, standardization, and better asset utilization, all parts of overall asset management strategy. This is the key to increased reliability and to protecting investments. Prudent capital investment in power system infrastructure has to be based on stringent cost-benefit analysis to optimize investments. For example, increase in generation ("conventional" or renewable energy) has to be planned in conjunction with strengthening the transmission grid. Holistic, multi-year system planning is required to achieve efficient, reliable, and cost-effective grid. In addition, independent certification of technical systems and business processes can be an important element of assuring that proper actions are taken, processes implemented, and investments made.

System Integrity Protection Schemes

Examples of large blackouts in the past decade have shown that the risk of large blackouts is no longer acceptable and can lead to very large and unexpected social and financial consequences. Reduction of the risk of large system-wide disturbances and blackouts requires that system protection function be approached with the assistance of modern technologies in support of preserving system integrity under adverse conditions.

These schemes, defined as System Integrity Protection Schemes (SIPS) [10–13], are installed to protect the integrity of the power system or strategic portions thereof, as opposed to conventional protection systems that are dedicated to a specific power system element. The SIPS encompasses Special Protection System (SPS), Remedial Action Schemes (RAS), as well as other system integrity schemes such as Underfrequency, Undervoltage, Out-of-Step, etc. These schemes provide reasonable countermeasures to slow and/or stop cascading outages caused by extreme contingencies.

SIPS goal is to prevent propagation of disturbances for severe system emergencies caused by unplanned operating conditions and ensure system security. They stabilize the power system for equipment outages, N-2 (two key elements out of service) or beyond by:

- Preventing cascading overloading of the lines and transformers
- Arresting voltage decline
- Initiating pre-planned separation of the power system

Advanced detection and control strategies through the concept of SIPS offer a cohesive management of the disturbances. With the increased availability of advanced computer, communication, and measurement technologies, more “intelligent” equipment can be used at the local level to improve the overall response. Traditional dependant contingency/event-based systems could be enhanced to include power system response based algorithms with proper local supervisions for security.

The IEEE Power System Relaying Committee has developed a worldwide survey on SIPS [12]. Figure 4.3 shows a summary of the overall SIPS purpose

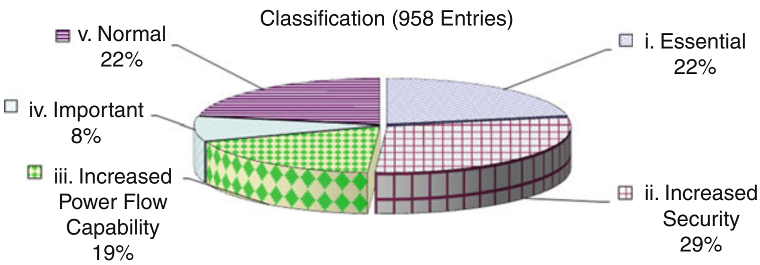

Fig. 4.3 SIPS classification

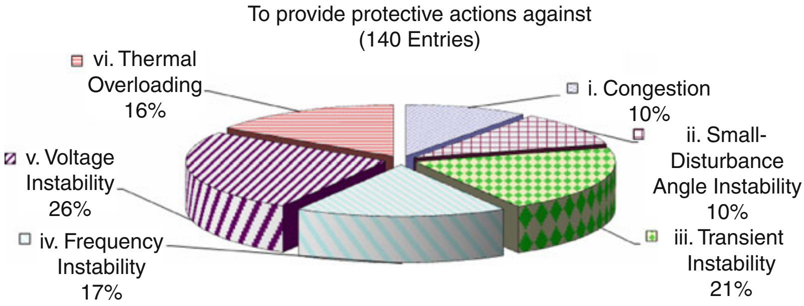

Fig. 4.4 SIPS purpose

classification. The numbers of SIPS performing similar types of functions have been grouped to indicate the total number of SIPS types. For each type of SIPS scheme, the number of schemes serving a similar purpose has been indicated, with the following classification:

1. Essential: Prevent cascading outages
2. Increased Security: Minimize area affected by undesirable conditions
3. Increased Power Flow Capability: To extend transmission system rating without adding new transmission facilities or to delay enhancement of transmission networks
4. Important: Avoid difficult operating conditions
5. Normal: A better functioning of the network

Note that almost all classifications are evenly distributed (with exception of "Important" which is at 8%). The approximate even distribution of classifications of SIPS highlights the important role of SIPS in grid reliability and how SIPS are integrated part of the grid development worldwide.

It is clear from Fig. 4.3 that the application of SIPS has become a component of a comprehensive total grid operation and protection philosophy. The fact that 22% of the entries are applications to address "normal" system conditions demonstrates that SIPS are no longer applied solely for system security purposes. In fact, close examination of Fig. 4.3 reveals SIPS applications can be viewed as two major categories:

- *Operational system improvement* (49% with three components: 19% Increased Power Flow, 8% Important, plus 22% Normal)
- *System security* (51% with two components, 22% Essential plus 29% for Increased Security) which at one time was the primary intent of SIPS

Figure 4.4 shows the intent of the various types of SIPS. The fact that voltage instability is the most often addressed phenomenon confirms that systems are now more complex than ever. The voltage stability phenomenon was firstly discovered at the beginning of 1980s as systems were getting more complex. The information in Fig. 4.4 correlates with the classifications in Fig. 4.3, demonstrating that worldwide SIPS are integrated components of various aspects of grid operation.

System Restoration

Another critical step in minimizing the impact of widespread blackouts is the need for effective and fast power system restoration. Returning equipment to service followed by quick restoration of power to the users is of paramount importance and can significantly minimize consequences of further outages.

Today's technology can be used to our advantage for intelligent restoration. Some of the key elements for responsive restoration are the following:

- Well-defined procedures that require overall coordination within the restoring area, as well as with the neighboring electric networks.
- Reliable and efficient restoration software tools significantly aid operators and area coordinators to execute operating procedures and to make proper decisions. This tool is a part of EMS/SCADA system that provides voltage, frequency, excitation, outage status, and other data.
- Regular training sessions to assure effectiveness of the process. These sessions should include practice drill scenarios. The drill scenarios should incorporate any regional reliability or governmental policy requirements. For example, there may be a time delay requirement for load restoration after bulk power system has returned to service, to allow the system to stabilize. There may also be critical loads, which must be given higher priority in restoration.
- Substations need to be manned to open breakers or switches to clear re-energization pathways and establish ability to control load restoration.

Today's technology allows us to propel in designing schemes to aid in quick restoration. Even if advanced tools and procedures are in place to speed up restoration, there are limits on how fast the system can be restored depending on the type and distribution of generation. After the August 14, 2003 blackout in North America, it took considerable time to restore generation. Some of the units did not have capabilities to be put in service immediately (black-start capabilities), and some units required longer time to be put on-line with full power (e.g., nuclear units due to security and steam turbines due to allowable ramp-up rates). Also of equal consideration is the type of load served, the system configuration, and the effects of connecting the load back to the network (Cold Load Pickup or Hot Load Pickup affects end user restoration time). While most of the cities have been restored in 5–9 h during the Italian blackout in September 2003, it took over a day to restore power back to Detroit and New York. Göran Andersson points out that in the recent Swedish-Danish blackout, the 400 kV grid was restored within 2 h, most customers were connected within 4 h, and the last customer reconnected within 6 h.

Mayer Sasson explains the slower pace for load restoration experienced in New York. The low-voltage network loads in New York City and Manhattan area are a highly meshed network system that affords a very high degree of reliability against localized outages. However, under blackout conditions, when a network is to be restored, the network is isolated into 100–200 MW portions that need to be re-energized at a time, requiring a time-consuming and careful process such that the inrush does not provide a set back to the restoration effort.

As discussed before, by designing the power system to transfer power across large distances and not providing enough reactive power close to the load or building the accompanying transmission lines may have detrimental effects on power system operation. Similarly, designing the power system not considering the effects on restoration efforts may have detrimental effects on the speed of restoration. In conclusion, restoration time and system security could be significantly improved by planning of the generation mix and location considering not only market factors but incorporating value of reliable operation and faster restoration in the financial model. This approach would result in optimal, long-term investment strategies.

Future Directions

As the power grids worldwide have become more complex and are operated closer to the operating limits, applications of Wide Area Monitoring, Protection, and Control (WAMPAC) systems have become necessary to better manage the grid reliability and performance security [15]. Control areas within the interconnected grids or among countries are recognizing that bulk power systems should be treated as one system and power system professionals are challenged to upgrade the system with technologies that makes the task of grid control manageable. New technologies such as synchronized measurements have advanced to support commercial WAMPAC deployment so that implementation of various applications is both possible and warranted, representing prudent investment.

Although large-scale demonstrations of using this technology are reported around the world, full-fledged productized systems have just started to be deployed. In the USA, those initiatives have been driven by transmission "smart grid" investments supported by DOE stimulus grants and NERC. WAMPAC systems using synchronized measurements have some unique deployment challenges as they require engagement of multiple users with diverse requirements and varying needs. Such large-scale systems not only offer a lot of promising reliability and financial benefits but also push the boundaries of conventional grid operations.

Synchronized measurement applications, using GPS synchronized Phasor Measurement Units (PMUs), offer large reliability and financial benefits for customers/society and the electrical grid when implemented across the interconnected grid. As measurements are reported 20–60 times per second, PMUs are well suited to track grid dynamics in real time. Compared to current EMS monitoring tools that use information from state estimation and SCADA over several second intervals, time-synchronized PMUs introduce the possibility of directly measuring the system state instead of estimating it based on system models and telemetry data. If implemented

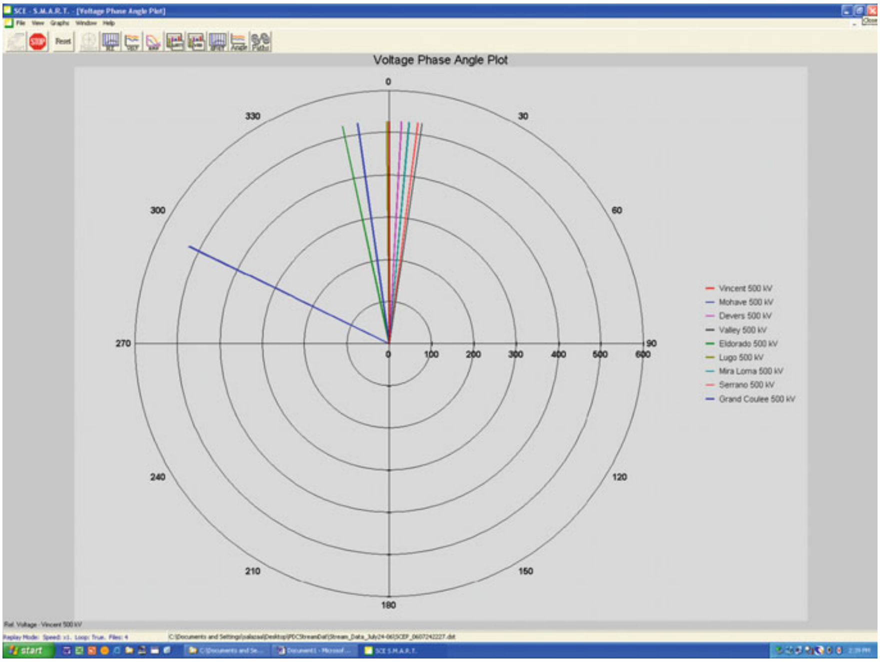

Fig. 4.5 Key system voltage angles – WECC disturbance on July 24, 2006

properly, the technology also allows for providing data integrity validation without added cost. This technology is instrumental for:

- Improving WAMPAC in real time including applications such as early warning systems, SIPS, detection and analysis of system stability, etc., and enabling faster system restoration
- Faster and more accurate analysis of vast number of data during transient events
- Validation and development of power system models

All of the above helps with avoidance and analysis of outages that may have extreme manifestation in blackouts. Due to its accuracy and wide-area coverage, synchronized measurement technology is a paradigm shift enabling unique tracking of power system dynamics. Synchronized measurement applications enable true early warning systems to detect conditions that lead to catastrophic events, help with restoration, and improve the quality of data for event analysis.

The display shown in Fig. 4.5 is a dynamic angle display during the disturbance in the western part of the USA in 2006. Those types of displays are used both for post-disturbance analysis and as an operational tool to help during the disturbance.

The conceptual WAMPAC system has interesting parallels with the human nervous system. Figure 4.6 shows the simplest concept of a WAMPAC system that spans a complete utility transmission system, or even an entire unified operating region. This conceptual description focuses on likely future implementations, without

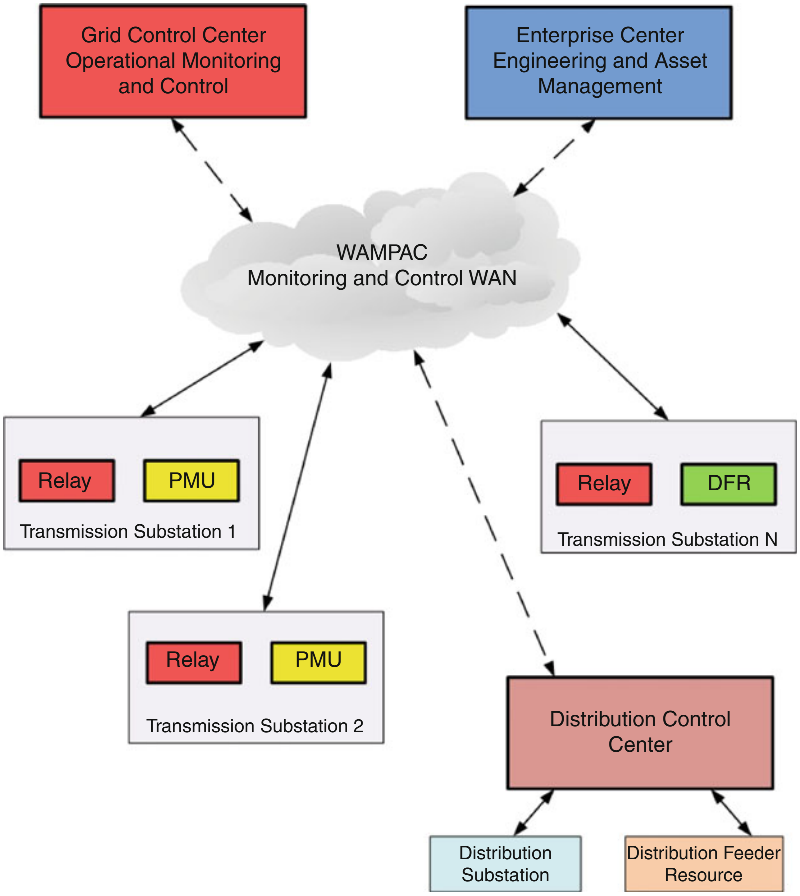

Fig. 4.6 Basic conceptual WAMPAC system

concern of integrating today's persistent but obsolescent components like independent SCADA RTUs. WAMPAC is in fact ultimately capable of absorbing all of the functions of today's SCADA and EMS, including not only measurement and control but also state estimation and real-time contingency analysis.

In summary, Wide Area Monitoring, Protection, and Control (WAMPAC) is a must for transmission smart grid as it is necessary to increase probability to prevent blackouts by improving following applications [15]:

- Data analysis and visualization – Significant benefits are achieved with the ability to analyze events much faster in a synchronized fashion on-line or post-mortem.
- System reliability improvement by preventing cascading outages due to voltage, angular, and frequency instability, thermal overloads, and low frequency oscillations – These applications result in huge societal benefits.

- System operations and planning, improved modeling – Synchronized measurement enables paradigm shift with high reporting rates not available with any other technology and in developing accurate power system models.
- Market operations: Congestion Management and Locational Marginal Pricing – These applications enable large financial benefits by better grid utilization.

With today's technology, it is possible to tie all the monitoring, control, and protection devices together through an information network. The key to a successful solution is fast detection, fast and powerful control devices, communication system, and smart algorithms.

Conclusions

Power system is very complex and human-made. Our industry needs to keep planning, operating, and maintaining it as efficient and as reliable as possible, including preventing blackouts. There is a general understanding of blackouts caused by natural disasters (earthquake, hurricanes, etc.). However, system-wide outages created by humans and/or not arrested due to suboptimal design should be easier to prevent. Analysis of large disturbances reveals some common threads among them, leading to the following conclusions:

- Need to understand the symptoms and root causes of the major disturbances and learn from the past blackouts.
- The power grid should not be operated under system conditions that have not been studied.
- Implement specific solutions to reduce the likelihood and propagation of outages.
- Restoration time could be reduced.

In summary, although it is not possible to avoid multiple contingency initiated blackouts, the probability, size, and impact of wide-area blackouts could be reduced and the propagation stopped.

Although electrical industry (utilities, ISOs, generation owners, regulators, universities, etc.) takes major initiatives after blackouts (such as investments in "smart grid" technologies), grids around the world always face host of new and old challenges. Applying a patchwork of individual measures to manage the grid is not sufficient. It is necessary to take a balanced approach to fixing the system as a whole by implementing a well-defined and coordinated overall strategy including various planning, operations, maintenance, and regulatory measures, weighing the costs, performance, and risks associated with each measure. It is important to always envision how power system should operate 10–30 years in the future; then design and overhaul it with this forward-looking approach.

Within the context of this approach, specific solutions to reduce the likelihood of outages can be addressed – because once the overall causes of wide-area disturbances are minimized, the smaller contributing factors are easier to handle, further diminishing the incidence of failures. The advent of advancements in information technology (IT), innovations in power system monitoring, and deployment of advance warning systems enables tools to arrest the grid from wide-area blackouts and meet the expectations for reliable power delivery. For example, while investing in strengthening the electrical grid infrastructure, such as rebuilding T&D grid and installing new generation and controls (e.g., reactive power devices, FACTS, HVDC), could not be replaced, "smart grid" WAMPAC deployment is necessary and cost-effective way to improve grid reliability. Under normal conditions, and with sufficient automatic supports, operators are able to adequately control power system operation. However, the speed and complexity of disturbance phenomena makes control of the grid more suited to automated WAMPAC systems to respond to fast developing and complex disturbances.

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