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MAJOR ELECTRIC POWER DISTURBANCES CAN BE TRIGGERED by storms, heat waves, solar flares, and many other sources, but all have their roots in the mechanical, cyber, and human vulnerabilities of existing power grids. As shown in Figure 1, 2012 was a particularly bad year for extreme weather in the United States. An aging grid infrastructure only exacerbates this problem by creating new concerns over energy reliability and grid resiliency. A single storm can cost billions of U.S. dollars in terms of direct damage to the grid, and it can cause significant power outage-related costs, including lost productivity.

It has been argued based on historical data and computer modeling that power grids are self-organized critical systems. These systems experience unavoidable disturbances that result in the loss of portions of the system or the entire system. This phenomenon has been attributed to steadily increasing load, reduced operating budgets and lower capital investment by power companies, and the technical limits of modern engineering.

“Power delivery systems have a lot of parts, wires, transformers, and other components all nicely tied together—which means there are a lot of things that can go wrong,” explains Clark Gellings of the nonprofit Electric Power Research Institute (EPRI). “Pieces break down, and people make errors. A system is designed to tolerate a certain amount of disruption, but past a certain point it’s simply gone too far, and it falls apart.”

EPRI has estimated that “across all business sectors, the U.S. economy is losing between US$104 billion and US$164 billion a year to outages.” By minimizing or eliminating interruptions, the self-healing grid could dramatically reduce this cost. Widespread blackouts, such as the 2003 outages in the United States and Italy, the 2006 outage in Europe, or the massive 2012 blackouts in India, are powerful reminders of the catastrophic consequences of power system outages.

Figure 2 shows the amount of load lost due to major blackout events in the United States for the years 1965 through 2003. All these blackouts had large adverse effects. For example, the Great Northeast Blackout of 1965, which began when a power surge in New York near the Ontario border set off a chain of failures across New York State and beyond, covered 80,000 mi². “Within four minutes, the line of darkness had plunged across Massachusetts all the way to Boston,” The New York Times reported on the day of the outage. “It was like a pattern of falling dominoes—darkness sped southward through Connecticut, northward into Vermont, New Hampshire, Maine, and Canada.”

The need for an automated, self-healing grid has grown in recent years as the complexity and vulnerabilities of the interconnected grid increase. At present, system operators “manually” perform power system recovery or restoration following a major outage based on guidelines from a restoration plan prepared off-line that may or may not accurately address the scenario actually taking place. Further, such restoration work is time-consuming and highly stressful for system operators. The complex tasks of emergency
Tools and Challenges for Smart Grid Restoration
recovery require advanced decision-support tools to enhance the resilience and, ultimately, the self-healing capabilities of a smart grid.

**The Need for Smart Restoration**

As shown in Figure 3, existing energy management systems (EMSs) have been designed to operate the power system in three states: normal, emergency, and restoration. In the normal secure state, all equipment is operating within limits and no critical contingency will cause real-time operating limit violations. In the normal insecure state, all equipment is operating within real-time limits, but one or more contingencies will cause operating limit violations. In the emergency state, some equipment is operating outside of real-time operating limits. The restoration state is in effect when there has been a major outage.

The restoration state may be entered either as a result of contingencies that cause loss of customer load or as a result of deliberate control actions taken to shed load in a portion of the system. Control actions in the restoration state should be designed to steer the system back to the normal state but could inadvertently transition the system to an emergency state. Current EMS applications focus on providing operator decision-making tools for the normal secure and normal insecure states. There are few real-time tools that have been designed to support operator decision making when the power system is undergoing a restoration process in the restoration state.

The development of smart grid technologies has been rapid as regards phasor measurement units (PMUs), special protection schemes, and wide-area situational awareness. It is time to further advance system restoration efforts so as to realize a self-healing grid with the aid of these technologies.

**Large-Scale Restoration Drills**

Since the 2003 Northeast U.S. blackout, a number of North American Electric Reliability Corporation (NERC) reliability coordinators and transmission operators have been staging comprehensive restoration drills. To support these drills, customer-specific models of individual power systems are built that include models of substation breakers; switch and bus configurations; models of the transmission system lines, transformers, and relays; models of the generators and prime movers; and models of the system loads. Models can be built by importing standard CIM/XML or PSSE data formats.

The customer’s supervisory control and data acquisition (SCADA) and automatic generation control (AGC) functions are emulated (rather than replicated) using the custom simulator software. The custom simulator’s SCADA one-line displays can use the same symbols, conventions, and layout as the real displays. The full model for a customer’s system often has several thousand buses and several hundred station one-line displays. This model can be set up and accessed by either a portable server or a Web server over the Internet.

Restoration drills are highly realistic and designed so that the reliability coordinators, transmission operators, and balancing operators can work with the substation operators, generator operators, and distribution operators to restore the system.

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**Figure 1.** Extreme weather and climate disasters in the United States. (Source: NOAA.)
from a complete or partial blackout. The lessons learned from these drills have demonstrated the difficult challenges of managing electric islands. This has served as a catalyst for new ideas about how smart grid technologies may be able to automate and expedite future system restoration procedures.

**Smart Restoration**

“Decision support tools must be highly flexible and adaptive to allow ever-changing power grid conditions to be reflected through seamless collaboration between human operators and computer-based optimization tools,” says Chen-Ching Liu, of Washington State University. Power system restoration following a widespread outage is a highly complex task for both planners and operators. Decision-making or decision support tools are therefore in great need for both online and off-line purposes. Decision making for power system restoration was among the earliest applications of intelligent system techniques. The progress of such tools has been slow, however, particularly for the online environment. One major hurdle is that the decision-making tools may not have sufficient information about the status of power grid elements as system restoration progresses. As a result, the recommendations from the decision-making tools may be inaccurate or obsolete. A simple example is the status of unmonitored manual switches or breakers. Dispatchers are in contact with field crews, so the status of these devices is known to them—but there is no mechanism for updating the status for the software decision-making tools in a timely manner. It is important that software tools play the role of decision support while the decisions themselves are made by dispatchers. In other words, software tools provide computational and logic-reasoning information for the various options dispatchers are considering. Making this adjustment requires closer collaborations among dispatchers, restoration planners, and smart restoration tools.

The other challenge of designing smart restoration tools is including the capability to adapt to different power systems and their respective system restoration strategies. Even for the same power grid, the outage conditions and the availability of power system facilities can vary significantly. A smart restoration decision support tool must be able to meet the needs of different power systems and various grid operating conditions. Based on the results of recent EPRI projects, the concept of generic restoration milestones (GRMs) has been developed, and the corresponding software modules have been tested with scenarios from large power grids. These decision support tools relieve the dispatchers from tedious tasks and ensure that detailed simulations are performed before decisions are made. We believe that the GRM decision support software tools represent a breakthrough in concept and technology development for smart restoration.

The GRM concept provides a methodology for developing smart software tools for decision support during power system restoration. The actual implementation will be enabled by emerging smart grid technologies. Although power system restoration involves a large number of generators, transmission and distribution facilities, loads, and system constraints, the actual restoration process can be broken down into a number of distinct phases. Each of the phases and the associated technologies that enable smart restoration is reviewed below.

**figure 2.** Major blackout events in the United States and their associated impacts in terms of load lost. NE = Northeast; NYC = New York City; WSCC = West Coast; MW = Midwest.

**figure 3.** The operation states of a power system.
Assessment of Power System Conditions
Following a major power system disturbance, the first priority is to assess system conditions. This critical task involves answering several questions:
✔ What are the statuses and characteristics of all generating units online or tripped off-line?
✔ What are the statuses of neighboring power systems and tie lines?
✔ What, if any, system load is still being served?
✔ If portions of the system are still energized, are frequency, voltage, and equipment loadings within acceptable limits?
✔ What are the boundaries of any islanded systems?

Identifying Electrical Islands
Methods are needed to accurately and reliably identify the extent of electrical islands. The identification can be accomplished using a combination of breaker and switch statuses with phasor measurements.

In the first pass, the electrical islands can be determined by running a conventional network topology program on the measured breaker and switch positions. In the second pass, dynamic PMU quantities can be compared over time and the buses that are in the same electrical island can be identified.

EMS overview displays have the ability to show different islands in different colors. Warnings can be provided in the event that a system operator selects a breaker that will connect two islands. Summary displays can also show the amount of generation capacity, which generators are connected, and the load that is connected in each island.

Topology and State Estimation
A successful restoration plan relies on accurately tracking network topology. Topology error identification has historically been performed manually as a post processing step following the convergence or nonconvergence of the state estimator. The errors in breaker and switch status can be detected by means of highly reliable PMU data. As a result, operators can avoid mistakes that may lead to another outage event.

Preparation of Subsystems
Before starting the actual restoration of the power system it is necessary to take several preliminary steps. For generation that has remained online, operators must
✔ adjust the voltage and frequency of online generators so they are within acceptable limits
✔ place AGC control in manual mode if it has not automatically tripped to manual mode
✔ address any power system overloads quickly, so that all equipment is operating within acceptable limits
✔ establish appropriate levels of operating reserve as soon as possible.

For generators that have recently tripped, operators must
✔ establish, if possible, a source of on-site power for each generator’s auxiliary loads
✔ ensure that the generator has safely shut down (a list of items to check for each generator should be included in the generator’s restoration plan)
✔ review any generator alarms for relevant information
✔ determine whether the generator is available for restart.

For generators with black-start capability, operators must
✔ review any generator alarms for relevant information
✔ check that the generator is available for restart
✔ start any necessary on-site emergency generation for the generator’s auxiliary equipment
✔ prepare the generator for a black start.

For generating units that are not in service, operators must
✔ review any generator alarms for relevant information
✔ check the availability of the generator for start-up.

Dead Bus Clearing
In the dead bus-clearing phase, the circuit breakers connecting two dead buses are “all opened,” with the goal of ensuring that equipment can later be energized without any risk of inadvertently connecting unplanned load or line charging. For a large system, this phase may take several hours. Some utilities have implemented special relays in the substations or group control procedures on their EMSs to minimize the time and operator involvement for this step.

Restoration Building Blocks
A restoration building block is a minimal configuration with a stable source of power. One example is a black-start unit or an energized interconnection point with some associated transmission that can serve as a viable subsystem for rebuilding the overall power system.

A restoration building block should have the following characteristics:
✔ a black-start capability sufficient to restore light and power to critical equipment
✔ the ability to match generation to load within frequency limits

With the implementation of such decision support tools, the power grid will be better prepared and equipped to handle extreme events.
adequate voltage controls and ability to dynamically provide megavars (Mvars) to maintain voltages within limits

the capability of being monitored at the system control center.

The capacity of a restoration building block to affect the overall restoration plan can be measured in two ways:

- The total MW capacity of the generating units will determine the amount of load that can be energized.
- The total Mvar absorption capability and the source impedance of the generating units will determine the length of the EHV transmission lines that can be energized.

Restoration building blocks have always been formed by using a single generating unit or power plant. The amount of transmission that can be energized is then limited by the Mvar absorption capacity of the black-start generating units as well as the minimum source impedance required to prevent transient over voltages. With phasor measurements and advanced governing control systems, it is feasible that a more extensive transmission corridor could be energized by simultaneously synchronizing generating units at multiple locations. The multiple generators would be able to combine their Mvar absorption capability so that a greater span of transmission circuits could be energized.

Expansion of Electrical Islands

Once one or more stable restoration building blocks are built, these can be expanded as electrical islands. The number of generation-load islands that can be built in parallel is usually matched to the number of control desks that are involved in the restoration. The expansion of each island requires the focused attention and supervision of one or two power system operators. The size of the islands can be determined in the planning stage, or they can evolve based upon the progress made by the crew at each operating console.

Current restoration methods use a manual approach to controlling the frequency of electrical islands. A single isochronous unit is designated for each electrical island. The unit operator monitors the unit frequency and manually controls the governor reference motor to maintain the island at the designated frequency. Automatic island frequency-control programs can be developed to control multiple units in an island to ensure that frequency deviations following the addition of load blocks are minimized. Prior to adding load blocks, the automatic island frequency-control program may direct the units to preposition frequency to a value greater than 60 Hz. This will increase the minimum frequency value that occurs after the load is added and thus limit damage to steam unit turbine blades.

Combine Electrical Islands

Electrical islands are currently tied together using breakers with synch-check relays. The frequency difference between the islands needs to be minimized in order to control the synchronizing angle and limit the flow between the islands after synchronization. Some utilities prefer to perform the synchronization at generating stations since the operators at these stations are more familiar with the operation of synch-check relays. A virtual synchroscope could be developed based on phasor measurements and power and angle calculations to remotely monitor any breaker in the system. The virtual synchroscope would allow synchronization operations to be performed manually or under program control from a remote location using any breaker in the system.

Reintegrate with Neighboring Systems

Integration with neighboring utility systems offers the opportunity to significantly increase the amount of online generating capacity and system inertia. This may greatly increase the overall stability of the system and its ability to withstand major contingencies, such as the trip of a large generating unit.

Integration with neighboring systems requires coordination between different transmission operators and often requires review and approval by a regional transmission organization. The frequency difference between the systems also needs to be minimized in order to control the synchronizing angle and limit the flow between the systems after synchronization.

Ferranti rise is a function of line length. Figure 4 shows the voltage at the open end divided by the voltage at the close end. A quadratic approximation provides a useful rule of thumb. A Ferranti rise of 5% occurs for lines of 150 mi. A Ferranti rise of around 20% occurs for lines of 300 mi. If a line is simultaneously energized from both ends, the Ferranti rise at the midpoint will be 25% of the Ferranti rise when energized from just one end. By arming breaker operations to occur simultaneously and by adding a synchroscope to measure the angle difference between buses at the ends of the line, it is possible to synchronize islands with very long lines while limiting the Ferranti rise at the midpoint.

Complete Restoration of Customer Loads

Load is typically restored based on the technical needs of the power system. Initial load restoration is focused on providing load to online generators, dampening voltage transients, and consuming excess Mvars. The loads restored are
selected based on size, ability to be quickly switched, and location in the energized system. Higher-priority customer loads are typically energized once system conditions are such that they can be accommodated. Care must be taken to ensure that in the haste to restore high-priority loads the energized system is not placed in jeopardy of another shutdown. As the restoration progresses, additional loads are picked up based on their relative priority. As more substations are energized, larger blocks of load can be reliably picked up by online generating units. Frequently, a gradual transition occurs from picking up load based on technical needs to picking up load based on load priority. There may be a need to strip some of the load from heavily loaded feeders before they can be restored to service. Eventually, customer loads are picked up based exclusively on load priority.

The Road to a Future Self-Healing Grid
Global positioning satellite (GPS) technology needed decades to become commercially utilized in navigation systems. Similarly, advanced technologies will be applied to system restoration applications in a gradual manner.

Developing Decision Support Tools for Restoration Planning
This first stage is to develop an off-line decision support tool for restoration planning. The major task is to develop tools for finding the sequence of generating units, transmission lines, and loads to be put online during a system restoration. For instance, the well-known node-branch-based power system model can be employed. Many widely used power system analysis tools are built on this model, which can describe the topology of a power grid. As a multistage and multiobjective problem, it is difficult to establish a uniform model to cover all constraints and objectives, however. An alternative methodology is to separate the problem into a series of subproblems. By integrating the results of each subproblem, an optimal strategy for a system restoration may be constructed with an acceptable outlay of computing time. During this process, the various characteristics of generating units, loads, and branches should be carefully modeled and reflected in analyses so as to meet steady-state requirements and both electromechanical and electromagnetic transient constraints.

Prototype off-line decision tools have been developed. For instance, with support from EPRI, a toolbox called System Restoration Navigator (SRN) has been developed based on the GRM algorithms. Currently, the main objective of SRN is to establish a feasible sequence, with acceptable duration, for cranking all non-black-start (NBS) generating units and picking up all critical loads. There are three running modes of the SRN core algorithm: automatic mode, which tries to find a feasible restoration sequence; iterative mode, which tries to crank one generating unit or critical load assigned by the user (SRN figures out the whole restoration sequence step by step,
with iteration input from the user); and advisory mode, in which, as in iterative mode, the restoration sequence is calculated step by step. The enhancement offered by this last mode is that SRN will provide an optional set of NBS units and critical loads. The components in this set can be restored successfully in the next step. This helps the user filter out infeasible restoration actions in the coming step. For all these modes, SRN checks the steady-state constraints and the electromechanical transient stability constraints for each step.

**Updating Decision Support Tool for System Operators**

Once restoration tools are available for planning, the next stage is to bring the decision support system for the planner closer to real-time online application. With a sufficiently detailed physical power grid model including breakers, switches, busbars, and so on, the established restoration strategies can be used by system operators after an outage. In this stage, more realistic system models and more constraints are to be taken into account in the dispatchers’ point of view.

EPRI has a two-phase effort to integrate the SRN algorithms with an operator training simulator (OTS). In the first phase, the minimum path search algorithm has been implemented to find feasible and direct paths between black-start units and secondary units and to find the nearest load to bring generating units up to their minimum operating limits. The SRN algorithm can be used with the OTS in an operator advisory mode for training purposes. It can also be used with the OTS in automatic restoration mode—for example, to develop and verify restoration plans and build partially energized islands for training scenarios. In the automatic restoration mode, SRN can reduce the labor needed to verify restoration plans and create training scenarios by a factor of ten. In the second phase, the SRN optimal power flow algorithm will be used to mitigate overloads and voltage stability issues that may tend to occur in the later phases of a system restoration plan, where the loads are higher but all the transmission is not yet in service. The effort is shown in Figure 5.

The power and light company test system is used as an example. Table 1 shows a part of the sequence generated by SRN and the mapping to the simulator actions.

Following the instructions in Table 1, the dispatchers can execute dispatch actions via the one-line diagram in OTS and observe the consequence of each action (see Figures 6 and 7).

**Developing a Real-Time System Restoration Navigator**

The final stage is to develop a real-time system restoration navigator for online dispatch in response to extreme events. Such a navigator would have the ability to identify system status, efficiently compute the restoration action sequence, execute restoration actions automatically or under the instruction from dispatchers, acquire the system’s state following each restoration action, and so on. In other words, this navigator would serve as a core application: a closed-loop control in the system restoration process.

**Benefits and Challenges**

**What Are the Costs and the Cost Savings?**

The decision support system for power system restoration serves as the essential component for the future self-healing smart grid. As an extension of traditional power monitoring and control, it will integrate more advanced theory and technology. Part of the cost of the self-healing grid will be incurred in modernizing the grid infrastructure to support
self-healing. The benefits of the self-healing grid to society, utilities, consumers, and employers are likely to exceed the investments, however. These benefits are summarized briefly below.

**Economics**
- Improved system reliability can reduce the economic losses incurred by consumers when power is lost.
- Utilities can avoid the large lost revenues caused by high congestion or unplanned outages.
- More efficient operation makes the system more flexible, leading to reductions in electrical losses and maintenance costs.

**Security**
The self-healing characteristics of the smart grid can decrease the threat of unexpected attack due to self-healing technologies and the distribution of sources.
- More advanced monitoring, distributed energy resources, and demand response all contribute to a more robust system that is more resilient to cyber attack.
- The weaknesses of the smart grid can be identified by modern analytical tools and then integrated into the security plan.

**Safety**
The grid’s self-healing characteristics can enhance public safety. For example, quick restoration can provide the necessary electricity to critical loads like hospitals.

**Environmental**
Smart grids can support more green resources, which can reduce emissions substantially. In addition, the environmental impact of accidents like transformer fires and oil spills can be avoided by means of accurate equipment failure prediction and prevention.

**The Challenge of Variable Renewable Resources**
To accommodate higher penetrations of variable renewable energy resources, changes to traditional system restoration methodologies will be required. Fundamentally, conventional generation resources have relatively predictable operating performance. As a result, restoration strategies in the traditional energy paradigm are based on the assumption that the output of each generating unit is controllable or predictable. This assumption is questionable in systems with a high percentage of variable renewable energy resources. According to NERC, two major attributes of renewable energy resources will affect power system planning and operation: variability and uncertainty. Generally, however, a generating unit, whether conventional or renewable, should present several benefits to system restoration. These are summarized below.

**Black-Start Capacity**
Compared with the normal operating condition, the system is weaker during the beginning stage of system restoration, with less control over frequency and voltage. At present, variable energy resources are not recommended as black-start
To accommodate higher penetrations of variable renewable energy resources, changes to traditional system restoration methodologies will be required.

capacity. Some standards do not allow the reconnection of variable energy resources at the beginning of system restoration. Disconnection of wind generation units connected to the distribution grid is usually less strict than for units connected to the transmission grid, i.e., units on the transmission grid are disconnected at a smaller frequency deviation. When the frequency deviation reaches the threshold values of the units’ protection, they are automatically disconnected from the grid. Smart grid technologies, however, may permit utilities to use variable renewable resources for black starts.

Load Restoration
After the system is restored with sufficient strength, variable renewable energy resources can be used for load pickup. Variable energy resources could provide power to restore load as long as they satisfy all general requirements, i.e., those regarding voltage regulation, low- and high-voltage ride-through, effective inertia, controllability for ramping and curtailing output, and frequency control.

A sophisticated operating methodology should be established to meet the recent dramatic development of variable renewable generation, mainly in the form of wind farms. Otherwise, the integration of uncontrollable wind generation may have a negative impact on system restoration under the current system operation methodology. A European Union report on the coordination of transmission of an electricity disturbance on 4 November 2006 shows that the unexpected reconnection of uncontrollable wind capacity had a very negative impact, preventing the dispatchers in both areas from managing the situation effectively.

The following two suggestions therefore make sense from the point of view of power system restoration after a major outage.

✔ Sophisticated control methods should be used to improve the frequency and voltage response performance of renewable energy resources before they can be used in system restoration.
✔ Since the system is much weaker during system restoration, standards that are different from the regular operating conditions should be established to meet these critical requirements.

Other Considerations
The growing interconnections among different elements of the infrastructure (e.g., communications, economic markets, and transportation) and their complex interdependencies could cause a blackout and affect more than one critical infrastructure. Addressing this interconnected nature of infrastructure requires an even more integrated approach than is presently possible. A good example is the dependencies that exist among power, communications, and IT infrastructures.

Conclusions
Effective system restoration is an important step toward a self-healing smart grid. In the future energy paradigm, with a high penetration of renewable resources and responsive demands, variability and uncertainty will affect power system operating and recovery technologies. Smart restoration provides an adaptive and optimized strategy with which to make restoration decisions, one that will reduce restoration time while maintaining system integrity.

With the implementation of such decision support tools, the power grid will be better prepared and equipped to handle extreme events. They enable the streamlining of communication among all stakeholders, and they preserve knowledge and experience for future engineers.

For Further Reading


Biographies
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