MAINTAINING SYSTEM BLACKSTART IN COMPETITIVE BULK-POWER MARKETS

BRENDAN KIRBY and ERIC HIRST
Consulting in Electric-Industry Restructuring
Oak Ridge, Tennessee

Restructuring the electric-power industry may provide substantial benefits in customer choice and economic efficiency, but it presents new challenges for bulk-power reliability. The incentives to maintain and properly deploy system blackstart services that worked for vertically integrated utilities may not work when the system operator, the transmission system, and individual generators are in separate commercial organizations.

To understand how the power system could be restored after a major blackout in a restructured industry, we reviewed existing and proposed North American Electric Reliability Council (NERC) rules and interviewed experts from 25 utilities located in each of the regional reliability councils (Hirst and Kirby 1998); the Edison Electric Institute sponsored this work. Utilities differ greatly in their attention to blackstart planning, preparation, training, and testing. These differences are not justified by differences in technical requirements among utility systems.

While the conditions that require system blackstart, a complete collapse of a major portion of the interconnection, are fortunately rare, the societal and economic consequences are so great that a reasonable effort is justified in preparing to meet such a contingency. Meaningful (i.e., detailed) standards for system blackstart planning, training, testing, and performance do not exist. Adequate performance is currently assured by holding the vertically integrated utility responsible for the final result. In general, the utility empowers its system operator to compel heroic action from its generation and transmission resources and people when this service is required. The system operator evaluates the risk of damage to generators and other equipment versus the system's need for restoration and the utility's risk of incurring the wrath of regulators and customers.

The current system for assuring adequate system restoration will likely not work under restructuring. System blackstart requires the coordinated efforts of the system operator, the transmission system, blackstart generators, and the remaining generators. Where it was previously only necessary to determine if the overall restoration performance was acceptable (not always an easy task) now it is necessary to determine if the performance of each party is acceptable and to assign responsibility (i.e., blame) if the restoration does not occur smoothly and promptly. Separate generation, transmission and system-control entities will have to be compensated for the risks they take and the damages and costs they incur because of blackstart activities. Clear standards for required performance along with contractual relationships to specify each party's responsibilities and compensation will be required to maintain system reliability.

PHYSICAL REQUIREMENTS

Unlike many other engineered systems, the four North American power system interconnections are designed to be in continuous *synchronized* operation. Individual pieces of equipment are taken out of service for maintenance, but each interconnection as a whole is designed to run without interruption.

Nevertheless, the power system must be prepared for the rare occasions when all or a major portion of the system is forced out of service. This might be the result of a particularly severe disturbance resulting in the loss of stability and the need for many generators to shut down. If this occurs, the system must be able to be restored to normal operations as quickly as possible. This is called system-blackstart capability.

The principal function of system blackstart is to restore the power system; restoring service to customers is secondary. The importance of this distinction is that system blackstart does not start with a prioritized list of customers that are restored in order. (For safety reasons, restoration of power to nuclear plants is an exception.) Instead, restoration is designed to return generation and transmission to service as quickly as possible. Load is used, especially in the early stages, to maintain the stability of generation; it is the loads' locations and magnitudes that determine which loads are restored when.

System restoration requires four sets of resources:

- Blackstart-generating units (often hydro and combustion-turbine units) that can start themselves without an external electricity source and can then energize transmission lines, restart other generating units, and ultimately restore service to customers;
- Nonblack start generating units that can quickly return to service after offsite power has been restored to the station and can then participate in further restoration efforts;
- Transmission-system equipment, controls, and communications (including ones that can operate without grid power), and field personnel to monitor and rebuild the electrical system after a widespread blackout; and

System-control equipment and communications (including ones that can operate without grid power), and people to plan for and direct the restoration operations after such a blackout.

For system restoration to be effective there must be a well thought out restoration plan, training exercises, and verification testing. Because the exact condition of the system at the time of failure will not be known ahead of time, the plan must be flexible. A great deal of additional information (charging current for each transmission line, loads on each substation feeder, etc.) must be assembled and available to the system operator to support flexibility in blackstart operations.

Blackstart proceeds as follows: (1) the system operator determines the nature, cause, and extent of the outage and whether the blackstart plan should be implemented; (2) the system operator communicates with appropriate utility departments, neighboring utilities, and the regional reliability council; (3) loads are disconnected and the transmission system is sectionalized, either directly from the control center or by the system operator directing field personnel to perform the operations; (4) the system operator directs one (or multiple) blackstart generators to begin operation; (5) once such a unit has started itself, the system operator begins the complex process of re-energizing a portion of the transmission system and providing power to other generating units; (6) generators without blackstart capability return to service as soon as possible after offsite power has been restored to them to allow restoration of the overall system to continue; (7) the system operator directs the reconnection of loads to the system as additional generation is returned to service, initially to help stabilize the generation and later to restore normal operations; (8) as individual islands of balanced generation and load grow, the system operator coordinates their resynchronization into the interconnection; and (9) service is restored to the remaining customer loads. All these steps must protect equipment and personnel, and maintain voltages and frequency near their reference values.

The coordination problem of re-energizing the grid is complicated. Generators have minimum and maximum load limits (MW) and maximum ramp rates (MW/minute). As the first generators come back online, the system operator must provide sufficient load to keep the units above the minimum load limits but not exceed their generating capabilities, ramping limits, or voltage-control capabilities. It is difficult to balance generation and load when both, along with the system configuration, are changing rapidly. Real power load is obtained by re-energizing groups of customers. Timing is critical because of the overall need to restore the system rapidly but also because the nonblackstart generators are each coming online first as loads because of their auxiliary equipment, then increasing that load as they prepare to restart generation, and finally requiring load themselves when they synchronize to the grid and begin delivering power. The longer it takes to restore offsite power to nonblackstart generators, the longer it can take for these units to return to service. Such delays can occur because conditions at the nonblackstart generators deteriorate the longer they are without power to operate their auxiliaries.

The transmission system itself presents a dynamic reactive load. Transmission lines are highly capacitive when not loaded and voltages can easily become excessive. Generators and reactors are used to hold voltages down. Unfortunately, generators are less stable when they are absorbing large amounts of reactive power than when they are producing reactive power. The system operator must be aware of each unit's reactive capabilities and the loads that will be imposed as each transmission segment is energized.

Restoration usually involves restarting the system in several locations at once. As the restoration progresses, each island contains a growing generation and load balance. These islands must be synchronized to re-establish the interconnection. This process involves matching the frequency and phase angle of adjacent systems before closing the breaker to connect the systems. Normal operations are resumed when the entire system is reconnected and all load is restored. Depending on the extent of the blackout, damage to the system, and other load and generation conditions, restoration will take hours to days.

Selecting the blackstart generators is somewhat location dependent. Blackstart generators must be electrically close enough to the other units they are to help restart to be able to energize the transmission lines connecting the two plants and control voltages at both ends. The blackstart units must also have sufficient capacity and ramping capability to be able to provide the restart power required by the other units. The system operator determines how many units within the control area must have blackstart capability, where they are to be located, and how to use them in the event of a blackout.

Unit and system testing and exercises are performed for three reasons. First, they assure that the equipment is properly maintained and capable of performing the required task. Second, they train personnel (this is especially important because of the rare need for the service and the resulting inability to get useful on-the-job experience). Third, they test the plan itself. Posttesting and postsimulation analysis is performed to determine what improvements are required in facilities, equipment, communications, personnel training, or to the plan itself.

Three types of blackstart units are in common use. Hydro units are generally used, when available. They are usually quick starting, can often be started remotely, and generally exhibit stable and fast control. Hydro units are so well suited for blackstart that NERC procedures recommend that all hydro units be equipped for blackstart capability. Frequently, a small (1 MW) turbine is included in the installation to power auxiliary loads, allowing the start of the main turbine(s).

Combustion turbines and internal-combustion-engine-driven plants (e.,g., diesel units) are often equipped with blackstart capability. These units can usually start rapidly, often under remote control, and can be precisely controlled.

Some thermal plants, while not capable of blackstarting themselves, can be equipped for load rejection. This technique relies on identification of the imminent collapse of the system, isolating the generator to its own auxiliary load (and possibly to some local load), reducing the generator's output from the pre-event operating level to match the isolated load, and maintaining that output until the system calls on the unit to connect to the grid, re-energize a part of the system, increase output, and help restart other units.

CURRENT PROVISION OF SERVICE

To identify how system blackstart is currently provided, we interviewed experts from 25 utilities located throughout the country. We also obtained documents from these utilities, and from a variety of other sources, including other utilities and NERC.

Testing of system restoration is generally accomplished by simulation or with a table-top exercise. Some utilities do no testing or simulation, while others (Union Electric, American Electric Power, and Southern) actually use blackstart units to energize portions of the grid (generally a single transmission line) and provide restoration power to a fossil unit. In England, the National Grid Company periodically tests the ability of blackstart units to restore service to nonblackstart generating units and for these nonblackstart units to then return to service quickly.

Utilities vary greatly in their treatment of blackstart. This range does not appear to be based on actual differences in system vulnerability or requirements. Geographically adjacent utilities often take very different approaches, suggesting that the key factor in designing a blackstart plan is the judgment and experience of those involved rather than probabilistic analyses of system failures.

COST COMPONENTS

We identified four types of costs associated with the provision of blackstart:

- Costs associated with blackstart units themselves. These include capital costs, testing costs, training costs, equipment damage costs, and fuel plus labor costs during actual blackstart operations.
- Transmission-system costs, including capital costs (telecommunications, synchronization capability, controls, emergency power for circuit breakers and facilities, etc.), planning and engineering costs, training costs, and personnel costs during an actual event.
- System-control costs, including capital costs (e.g., telecommunications, computers, and emergency-power systems) and operating costs for planning, testing, and training.
- Costs at nonblackstart power plants to enable them to restart quickly once offsite power is restored as well as equipment-damage costs (e.g., damage to the turbine because of operation at frequencies too far from 60 Hz) incurred during an actual event that results from returning to service too quickly.

Obtaining estimates for these costs was difficult. Utilities have not accounted for these costs in an easily accessible fashion. It is also difficult to unambiguously assign system-operator and transmission-system costs to system blackstart. The utilities felt that system-blackstart requirements do not influence personnel requirements at the control center. While many people are required in the field to verify conditions and perform operations, these people are already employed by the utility. It is also hard to pin down control-center or transmission-system capital costs that can be attributed to blackstart requirements. Emergency power for the control center, for example, is required in case the control center's primary power supply is disabled. This could happen (and is most likely to happen) even if the rest of the power system is viable. The same is true for backup power supply for the rest of the system. Communications and control systems must be redundant and survive even if their primary power supply is disabled. Transmission circuit breakers must be capable of a limited number of operating cycles (typically open-closed-open) without external power support. None of these costs is incurred exclusively for system blackstart. Only a few costs, such as providing synchronizing capabilities at selected locations on the transmission system, can be attributed solely to system blackstart.

Costs associated with providing blackstart capability to generators are conceptually easier to identify and associate with the blackstart requirement. Still, we were not able to obtain many cost figures because generally utilities do not track these costs. Costs associated with nonblackstart generators returning to service are even more elusive, although no less real.

Houston Lighting and Power estimated that provision for blackstart capability might add $1 million to a $100 million fossil plant. Annual increased labor cost is modest as well, perhaps $0.1 million. It blackstarts one unit a year using 30 to 40 people to gain experience. Southern estimated the cost of adding blackstart capability to a $25 million, 80-MW combustion turbine at $0.1 million.

CURRENT STANDARDS

NERC (1997b) delineates required actions in various policies. System restoration from a blackout condition is addressed in Policy 5E: Emergency Operations – System Restoration and in Policy 6D: Operations Planning – System Restoration. Policy 5E specifies the following:

> After a system collapse, restoration shall begin when it can proceed in an orderly and secure manner. Systems and control areas shall coordinate their restoration actions. Restoration priority shall be given to the station supply of power plants and the transmission system. Even though the restoration is to be expeditious, system operators shall avoid premature action to prevent a re-collapse of the system. Customer load shall be restored as generation and transmission equipment becomes available, recognizing that load and generation must remain in balance at normal frequency as the system is restored.

Policy 6D requires "each system [to] develop and periodically update a logical plan to reestablish its electric system ... . A reliable and adequate source of startup power for generating units shall be provided. ... Generation restoration steps shall be verified by actual testing whenever possible. ... System restoration procedures shall be verified by actual testing or by simulation."

NERC's (1997a) Planning Standards also address system blackstart (Section IVA) by, again, requiring "a coordinated system blackstart capability plan" and requiring that blackstart generators demonstrate their capability once every five years "through simulation or testing."

NERC's (1998) proposed Policy 10 improves upon the existing NERC guidance by including requirements for certifying and testing blackstart units themselves. Unfortunately, the policy does not address any system control, transmission system, or nonblackstart unit requirements. Nor does it address training, simulation, or exercises.

While the guidance currently offered by NERC is helpful, it may not be enough for a restructured industry where competitive entities must be organized and act cooperatively to address a system emergency. NERC offers little detail concerning either the required response that the service is supposed to deliver or the resources that should be dedicated to service provision. NERC provides no specifics on the number of generating units that should be blackstart equipped, how to determine this, or how quickly blackstart units should respond. It says nothing about how often the system restoration plan should be tested or what should be included in such tests.

STANDARDS UNDER RESTRUCTURING

In a restructured electricity industry, it may be appropriate to have separate standards for each of the four components of system blackstart. Such standards could include the following elements.

System Operator: The system operator will, at least once a year, simulate system restoration using information on blackstart generation, transmission, nonblackstart generation, load, and the restoration plan. The regional security coordinator will certify the restoration plan only if the simulation demonstrates a high probability that restoration will be successful. Simulations and training exercises will include operating personnel from system operations, transmission operations, blackstart generators, and nonblackstart generators. The exercise will be conducted in the facilities the personnel will be working in during a restoration using the communications equipment that will be available during such a restoration. The entire restoration plan will be simulated with each party reporting on actions they would take in a restoration. A computer simulator will be used to determine the expected response from the power system to each action taken.

Transmission System: The system operator will certify the transmission provider's capability (personnel and equipment) to support the blackstart plan. The transmission provider will supply the control-area operator with detailed information concerning the transmission blackstart capabilities and requirements of all equipment on the transmission system. This information shall include: charging current, control capability without support from the grid under manual and automatic control, communications capability with and without grid support, personnel available for emergency response to restore the system, and availability of synchronization and other special equipment to restore the system. Communications, metering, and control systems must be capable of operating without support from the power system with sufficient capability to support the system blackstart restoration plan.

Blackstart Generators: In addition to metering and communications requirements, each blackstart generator will undergo separate starting tests, line-energizing tests, and load-carrying tests. The blackstart test, which will be conducted at least twice a year, involves isolating the generator from the power system, having the unit start itself within the agreed upon time of being directed to do so by the system operator, and then remaining stable (both voltage and frequency) for at least 30 minutes. The line-energizing test, which will be conducted at least every three years, will demonstrate the ability of the generator to energize a previously de-energized transmission line and to remain stable for at least 30 minutes. The load-carrying test, which will be conducted at least every six years, will demonstrate the ability of the generator to pick up sufficient load at the remote end of the isolated transmission system to demonstrate its capability to supply this load for at least 30 minutes.

Nonblackstart Generators: Each nonblackstart generating unit must prepare and submit to the system operator its restoration plan. The restoration plan will assume that the system failure was not the result of physical damage to or failure of this generator. The plan must specify the amount of time the generator requires, after the restoration of off-site power, before it is capable of synchronizing and picking up load. The plan must specify the amount of off-site real and reactive power required by each unit during the time it is preparing to return to service. The plan must specify the capabilities and requirements of the nonblackstart generator once it synchronizes to the grid including minimum load, maximum load, ramp rate, and reactive capability range at minimum and maximum load.

RESTRUCTURING

The lack of specificity in blackstart requirements presents a fundamental problem under restructuring. This lack of specificity, coupled with the need for multiple independent parties (generators, transmission owners, and the system operator) to work cooperatively makes it difficult to assign responsibility for failure of the final result (rapid system restoration). Hence, the current system of indirect regulatory pressure is likely to be ineffective.

In April 1996, the U.S. Federal Energy Regulatory Commission (FERC) issued its landmark Order No. 888 initiating restructuring of the electric power industry on a national level. As part of its program to unbundle generation from transmission, FERC required transmission providers to offer six ancillary services to transmission customers. FERC did not impose any requirements with respect to blackstart, perhaps assuming that the cost to provide this service would be incorporated in the basic transmission tariff. So little help is provided here.

Gaining the cooperation of all parties in preparing for and executing the activities required to restore the power system after a large-scale blackout is difficult because of the expense involved. On a systemwide basis, system-blackstart costs are surely quite low compared to total generation costs, but they can be quite high for an individual generator. A combination of technical requirements and economic incentives will be needed to assure successful provision of the service.

The system operator could likely procure blackstart capability competitively from generators. Technical restrictions concerning unit capabilities (speed of response, control capability, voltage control, etc.) may limit the number of suitable generators. Locational restrictions may further reduce the number of units that can provide this service (e.g., such units must be electrically close enough to other units to be useful in restarting them). But the predominant response from the utilities we surveyed was that often enough units meet (or could meet) the technical requirements to allow formation of a competitive market. Within reason, restoration plans could be adjusted to accommodate changes in the location of blackstart units.

To facilitate competitive procurement of blackstart services from generators, system operators would have to be explicit about the services such units are required to provide. This requirement would include the speed of response, minimum and maximum real and reactive capabilities, and ability to control frequency and voltage. It would also require that the system operator know what resources will be required at each location. The competitive assessment would evaluate technical feasibility, capital costs, testing costs, and costs during actual use of the service.

System-operator and transmission-system costs related to system blackstart, on the other hand, should be dealt with as are other system-operator and transmission-system costs. They will likely require FERC review to assure that they are prudent and can be recovered in regulated rates.

Individual nonblackstart generators may affect the cost of blackstart in two ways. First, the amount of offsite power required to restart units and the speed with which that power must be restored may differ. Second, generators may differ in the time it takes to return to service and begin supporting the power system once offsite power is restored. These differences can be a result of the generating technology employed as well as commercial considerations. Larger units, for example, require more power to restart. Consequently, blackstart units have to be larger. Other generating units may impose additional system-blackstart requirements. The location and controllability of nonblackstart units affect their value when restoring the system. How quickly off-site power has to be restored to other generators to avoid damaging the unit and greatly delaying the unit's ability to return to service may also differ. Compensating nonblackstart units for their costs associated with supporting system restoration could be difficult. Alternatively, provision of blackstart capability could be a requirement for connecting to the grid. We found little evidence that this cost differentiation has been recognized or is being addressed.

Nonblackstart generators could be required to return to service within a specified time after the system restores offsite power to them. This amount of time would depend on how long it takes the system to restore offsite power, recognizing that a generator will be in progressively worse condition the longer it remains without offsite power to operate auxiliaries and/or as the unit cools. Additional time may be required to restart each subsequent unit at a generating plant.

This type of specificity, which recognizes unit capabilities and system needs, is required in moving to a competitive environment. Since restoration events are very rare, economic incentives might not be sufficient in motivating response from the nonblackstart units. Simple requirements with strong penalties for failure to comply might be better. The incentives or penalties should recognize the benefit that the system receives from units that are inherently capable of fast and flexible response. This recognition could be accomplished through a combination of charges for system restoration at rates that reflect the burden or benefit the individual generator places on the system during restoration coupled with response requirements when the service is required.

CONCLUSIONS

While system blackstart is conceptually well understood and universally acknowledged to be important, its detailed requirements are difficult to pin down. For the system to require blackstart, something went badly wrong. It is difficult to quantify expected results from the blackstart service without prior knowledge of what will go wrong. Still, this does not explain the diversity among utility blackstart plans. The current system of indirect regulatory pressure on vertically integrated utilities will not work in a restructured environment. NERC's technical guidelines fall short as well.

Competitive markets could develop for blackstart capability. Reliability requirements restrict the locations and capability requirements for individual blackstart generators. However, if there are enough generators located so that they can provide the blackstart service, the competition among them may be enough to allow markets to determine the prices of this service. The control-area operator is the only buyer because it is responsible for determining how much of the resources to acquire and how to deploy them. The system-control and transmission portions of system blackstart cannot be provided competitively. These services, by definition, can be provided only by the monopoly entities that manage and operate control areas.

FERC views system blackstart narrowly, focusing on the ability of some generating units to self start. FERC apparently did not consider the transmission-system and system-control activities associated with this service. More important, FERC imposed no requirement on transmission providers to offer the service or on transmission customers to pay for it. And NERC's standards for this service lack specificity; they do not address the need for nonblackstart generators to aggressively support system restoration.

Possible ways to ensure continued provision of this essential service in a restructured electricity industry include (1) NERC developing more specific planning, testing, and operating standards for this service; (2) FERC recognizing system-blackstart as distinct from generator-blackstart capability; (3) FERC requiring transmission providers to offer and transmission customers to purchase this service; and (4) Providing the system operator with the authority to ensure that blackstart and nonblackstart generators, transmission owners, and the system operator itself provide and coordinate this service, which will require both technical requirements and economic incentives for generators and transmission providers.

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