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HydroWIRES

The US electricity system is changing rapidly with the large-scale addition of variable renewables, and the flexible capabilities of hydropower (including pumped storage hydropower) make it well-positioned to aid in integrating these variable resources while supporting grid reliability and resilience. Recognizing these challenges and opportunities, WPTO has launched a new initiative known as HydroWIRES: Water Innovation for a Resilient Electricity System. HydroWIRES is principally focused on understanding and supporting the changing role of hydropower in the evolving US electricity system. Through the HydroWIRES initiative, WPTO seeks to understand and drive utilization of the full potential of hydropower resources to contribute to electricity system reliability and resilience, now and into the future.

HydroWIRES is distinguished in its close engagement with the US Department of Energy (DOE) national laboratories. Five national laboratories—Argonne National Laboratory, Idaho National Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory—work as a team to provide strategic insight and develop connections across the DOE portfolio that add significant value to the HydroWIRES initiative.

HydroWIRES operates in conjunction with the Grid Modernization Initiative, which focuses on the development of new architectural concepts, tools, and technologies that measure, analyze, predict, protect, and control the grid of the future and on enabling the institutional conditions that allow for quicker development and widespread adoption of these tools and technologies.

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Executive Summary

During a power plant outage, a power plant operator can typically still rely on the electric grid to which the plant is connected to supply power for the plant's "house loads" (e.g., lights, data systems, telecommunications equipment) as well as for auxiliary equipment needed to start a generating unit or keep it running (e.g., oil pumps, gas compressors, draft fans, pulverizers, controls, switchgear, and sensors, safety and protection systems). In the event of a widespread outage, however, that electric grid may also be out of service and thus unavailable to provide needed power to any of the power generation plants within its service territory. This situation drives the need for a type of plant that is able to start its generator unit(s) from a completely unenergized state without the need for external power from the grid. This provisioning is called "black start."

This report identifies the advantages of using hydroelectric power for black start and compares hydropower with other types of power plants for providing this valuable service to ensure the resiliency of the power grid. The report provides an overview of the critical role of black start capability to ensure timely restoration of grid operation after a major power grid outage ("blackout"). It discusses the sequence of operations to black start (power up) a power plant and to restore the grid after a major blackout. In this context, the report discusses how the types, sizes, characteristics, and locations of black start–capable units affect the speed of recovery. In turn, the characteristics of various power generation technologies are compared with the attributes needed to quickly and efficiently power up a black start plant and re-energize the power system for normal operation.

The first sections discuss the fundamental steps in the black start sequence, from damage assessment, to powering up black start plants, to energizing areas ("islands") of the grid, to the final integrated interconnection of electrical grid islands. The steps needed to black start a power plant from an unenergized state include the following:

- A self-starting on-site power source provides station and startup power to energize control, safety, communication, and emissions control systems; restart cooling systems; and prepare fuel and fuel handling systems.
- Internal (to the plant) buses are configured for start-up.
- The turbine is started and brought up to speed to generate power from the generator.
- All generators are powered to bring the plant into operation.
- The power from the now-operating plant energizes the generator step-up transformers and connected transmission lines.
- System operators configure the transmission system to provide an electrical path ("cranking path") to other non-black start generators.
- Power from the newly re-started plant is used to provide station power to start up other generators.

The report provides a high-level review of the technical characteristics that are most important in a black start scenario for different types of power plants, distinguishing between plant-centric characteristics (i.e., specific to the features of a particular generating facility) and topological ones (i.e., referring to the environment around the plant and the plant's electrical connections to the transmission system [grid power delivery network] and other plants).

The characteristics that favor black start–capability for a generator include the following:

- Small station power requirements (e.g., lower power needed for systems for fuel handling, cooling, emission control, monitoring and control, communication)
- Fast restart (powering up the plant to its rated output)
- Large on-site real and reactive power capacity
- Adequate on-site fuel supply
- Ability to operate during frequency excursions
- Ability to stabilize system frequency (large size and inertia, high ramp rate)
- Direct transmission connections with other generating plants

Thus, the "ideal" black start unit

- Needs minimal time, fuel and equipment to restart
- Can be relied upon at any time to be available for black start, with fuel on hand
- Has sufficient nameplate capacity to provide real and reactive power to energize transmission and restart other generators
- Can provide station and start-up power to other generating plants/generators with a minimum of transformations (transformers in the path) and transmission switching operations
- Can operate quickly after a blackout during early grid restoration operations, can continue to operate when frequency swings are expected and occur, and can help stabilize system frequency

These desirable characteristics are analyzed for several power generation technologies, including the following.

- **Hydroelectric** power plants meet all the desired attributes for black start:
  - Except in the most extreme drought conditions, the reservoirs impounded by dams store enough water to power, without any special preparation, turbines for black start operation.
  - Minimal station power is needed, since fuel preparation and cooling are not required.
  - The plants that have backup power (e.g., small diesel generators) to manage spillway gates can also use this resource for black start.

- Hydro plants can restart quickly, with minimal internal preparation and buswork switching.
- Hydropower generators tend to be more tolerant of frequency excursions than large steam generators, and they also have significant inertia and high enough ramp rates (for changing power output) to help stabilize system frequency.
- Many hydropower generators are large enough to supply adequate power to energize the transmission system, provide station power to start up other generating plants, and pick up loads.
- Hydropower connections to the transmission network usually enable direction of their output to restart other power plants with minimal transmission line switching.

- **Pumped storage hydropower (PSH)** units have almost all the advantages of conventional hydro units. However, economical dispatch may deplete the upper ponds of PSH systems, so PSH units are not sure to have adequate energy available for black start unless some water is always held in reserve for it.

- **Combustion turbines (CT)** are typically well suited for black start.
  - They are fairly large.
  - They restart quickly with minimal preparation.
  - They are tolerant of system frequency excursions.
  - They can vary output quickly (ramp rate).
  - They usually have strong connections to the transmission network, enabling them to provide station power to other plants.
  - However, they depend upon having a (limited) supply of pressurized gas on-site and/or having the natural gas pipeline that supplies the CT plant pressurized and operating. That requires electricity.
  - CTs have cooling system requirements, but their cooling systems are usually simple and do not require a lot of power.
  - While the flexibility that their strong ramp provides can help stabilize system frequency, CTs do not have high inertia.

- **Combined cycle** units are usually larger than CTs, but they are less suitable as black start resources.
  - They require several hours to restart.
  - They have more complex cooling systems.
  - Like CTs, they require that the gas pipeline supplying fuel is in service and pressurized.

- **Coal-fired plants** are typically not equipped for black start.
  - On the plus side, they are large, have more inertia than the previous plant types mentioned, have fuel (coal) onsite, and typically engender a reliable and robust connection to the transmission grid.
  - However, it takes many hours to return their boilers to temperature to produce steam to turn the turbines.
  - They have large cooling systems (pumps, controls, and valves) that must be in operation before the plant can be restarted.
  - They have complex fuel processing and handling and emissions control systems that require much power.

- **Nuclear power plants** are not good candidates for black start, despite having very large generating units with onsite fuel supply and high inertia.
  - Nuclear units usually require several days to restart after they are powered down (the procedure includes numerous tests and inspections).
  - They have onsite backup power to supply station power if the plant trips offline, but it is used to power the reactor down safely after a loss of offsite power (LOOP) event.
  - The existing onsite fuel for backup power must be held in reserve in case it is needed to power down the reactor safely; additional fuel would be required for black start.
  - Nuclear Regulatory Commission regulations and safety concerns preclude restarting a nuclear plant if the grid is unstable (i.e., after a blackout) and there is a significant probability of a LOOP event after restart.

- Utility-scale **renewable energy power sources** (solar photovoltaic- and wind-powered generators) cannot be relied upon as black start resources.
  - They provide power only as available because they rely on environmental conditions, so there is no assurance they will be available when black start is needed. (i.e., it may be night or twilight; there may be heavy cloud cover; the wind may be not strong enough or too strong). Although many solar and wind farms are equipped with batteries, these are designed to smooth generator output variations and are not large enough to provide cranking power to restart other generators.
  - If conditions are such that a solar or wind installation can supply power after an outage, and it is equipped with suitable advanced inverters and controls, it could theoretically black start and provide cranking power to other generators. But because the availability of the resource is uncertain, as-available renewable energy cannot be considered a firm (reliable) black start resource for planning purposes.

- **Distribution-level battery energy storage systems** resources can be invaluable in restoring service to selected customers after an outage (e.g., supplying loads at industrial facilities or, at the feeder level, powering a microgrid that serves multiple customer loads). As the grid recovers and electrical islands are reconnected, having an energized and operating substation (and connected customer loads) will speed overall grid restoration. However, these installations are too small to be considered as black start resources that can provide station power to generators.

Hydropower plant characteristics are particularly well suited to ensuring that the power grid has adequate and appropriate resources to support black start operation. Historically, power systems have relied heavily on hydropower plants for black start capability. Hydropower continues to play a role in grid resilience because of its inherent ability to start quickly with minimal station service (the energy needed locally at a plant to power internal equipment) needed and because "fuel" from waterways and reservoirs is constantly available. About 40% of the units in the United States maintained and tested for providing black start are hydropower turbines, although hydropower makes up only about 10% of overall US generating capacity.

Acronyms and Abbreviations

BESS	battery energy storage system
CAISO	California Independent System Operator
CIP	Critical Infrastructure Program
CT	combustion turbine
EOC	emergency operations center
ERO	Electric Reliability Organization
FERC	Federal Energy Regulatory Commission
ISONE	Independent System Operator New England
ISO/RTO	independent system operator/regional transmission organization
LOOP	loss of offsite power
MISO	Midcontinent Independent System Operator
NERC	North American Electric Reliability Corporation
NRC	Nuclear Regulatory Commission
NYISO	New York Independent System Operator
O&M	operations and maintenance
PJM	Pennsylvania, Jersey, Maryland Power Pool
PSH	pumped storage hydropower
PV	photovoltaic
SCADA	supervisory control and data acquisition

Glossary

Auxiliary Load: The load at a power generating station, which includes ancillary equipment such as pumps, fans, and soot blowers used with the main boiler, turbine, engine, waterwheel, or generator.

Black Start Capability: The capability of generating units to start without an outside electrical supply or the demonstrated ability of a generating unit to automatically remain operating at reduced levels when disconnected from the grid.

Black Start Capability Plan: A documented procedure for a generating unit or station to go from a shutdown condition to an operating condition, delivering electric power without assistance from the electrical system. This procedure is only a portion of an overall system restoration plan.

Black Start Resource: A generating unit(s) and its associated set of equipment that can be started without support from the electrical system or is designed to remain energized without connection to the remainder of the system. Such a resource can energize a bus, meeting the transmission operator's restoration plan needs for real and reactive power capability, frequency and voltage control, and is included in the transmission operator's restoration plan.

Bulk Power System: (A) Facilities and control systems necessary for operating an interconnected electric energy transmission network (or any portion thereof). (B) Electrical energy from generation facilities needed to maintain transmission system reliability. The term does not include facilities used in the local distribution of electricity.

Bus: An electrical conductor that serves as a common connection for two or more electrical circuits.

Cascading: The uncontrolled successive loss of system elements triggered by an incident at any location. Cascading results in widespread electric service interruption that cannot be restrained from sequentially spreading beyond an area predetermined by studies.

Cold Load Pickup: The process of energizing load centers that have been off-line for an extended period.

Contingency: The unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch or other electrical element.

Cranking Path: A portion of the electric system that can be isolated and then energized to deliver electric power from a generation source to enable the startup of one or more other generating units.

Critical or Priority Load: Specific loads identified in a system restoration plan, whose prolonged interruption may have an undesirable impact on health, safety, and the environment and which are therefore targeted for early restoration. Priority load may include off-site power for nuclear generating stations (to maintain safe shutdowns), cranking power to certain generating units, power to natural gas infrastructure (such as electric compressors), power to pumping stations for oil pipelines, military installations and flood water control installations, and power to hospitals and other emergency operations.

Electrical Island: An electrically isolated portion of an interconnection. The frequency in an electrical island must be maintained by balancing generation and load to sustain operation. Islands are frequently formed after major disturbances wherein multiple transmission lines trip, or during restoration following a major disturbance.

Emergency: The failure of an electric power system to generate or deliver electric power as normally intended, resulting in the cutoff or curtailment of service.

Emergency Energy: Electrical energy provided for a limited duration, intended only for use during emergency conditions.

Emergency Generator: The electric generators used only during interruptions of normal power supply.

Forced Outage: (A) The removal from service availability of a generating unit, transmission line, or other facility for emergency reasons. (B) The condition in which the equipment is unavailable because of unanticipated failure.

Generator Operator: The entity that operates generating unit(s) and performs the functions of supplying energy and interconnected operation services. The generator operator is responsible for establishing procedures for starting each black start resource, in accordance with Reliability Standard EOP-005-2.

Independent System Operator: An electric power transmission system operator that coordinates, controls, and monitors the operation of the electrical power system, usually within a single US state but sometimes encompassing multiple states.

Inrush Current: The maximum, instantaneous input current drawn by electrical equipment such as a transformer or an electrical motor when it is first energized. Upon starting, electric motors draw about ten times their normal power level, dropping back to normal power consumption as they reach operating speed.

Interconnection: A geographic area in which the operation of bulk power system components is synchronized so that the failure of one or more such components may adversely affect the ability of operators of other components in the system to maintain reliable operation of the facilities within their control. When capitalized, any one of the four major electric system networks in North America: Eastern, Western, Electric Reliability Council of Texas, and Quebec.

Load: An end-use device or customer that receives power from the electric system.

Load Rejection: The condition in which there is a sudden load loss in the system that causes the generating equipment to be over frequency.

Load-Serving entity: Secures energy and transmission services (and related interconnected operations services) to serve the electrical demand and energy requirements of its end-use customers

Microgrid: A group of localized, interconnected loads and power sources that operate within a defined electrical boundary. A microgrid acts as a single entity and can disconnect from the traditional grid and operate autonomously in "islanded" mode.

Next Start Generating Unit: The first generating unit in the cranking path to be energized using power from the black start generating unit.

Open Access Transmission Tariff: Electronic transmission tariff accepted by FERC requiring the transmission service provider to furnish to all shippers with nondiscriminating service comparable to that provided by transmission owners to themselves

Reactive Power: The portion of electricity that establishes and sustains the electrical and magnetic fields of alternating-current equipment. Reactive power must be supplied to most types of magnetic equipment, such as motors and transformers. It also must supply the reactive losses on transmission facilities. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors and directly influences electric system voltage. It is usually expressed in kilovar (kvar) or megavar (Mvar).

Real Power: The portion of electricity that supplies energy to the load.

Regional Entity: An independent entity with delegated authority from NERC to propose and enforce reliability standards and otherwise promote the effective and efficient administration of bulk power system reliability.

Regional Transmission Organization: An electric power transmission system operator that coordinates, controls, and monitors a multi-state electric grid.

Reliability: A measure of the ability of the system to continue operation while some lines or generators are out of service. Reliability deals with the performance of the system under stress

Reliability Coordinator: The entity that is the highest level of authority; is responsible for the reliable operation of the bulk electric system; has a wide-area view of the bulk electric system; and has the operating tools, processes, and procedures—including the authority—to prevent or mitigate emergency operating situations in both next-day analysis and real time operation. The reliability coordinator has a purview broad enough to enable the calculation of interconnection reliability operating limits, which may be based on the operating parameters of transmission systems beyond any transmission operator's vision.

Reliability Standard: A requirement, approved by FERC under Section 215 of the Federal Power Act, or approved or recognized by an applicable governmental authority in other jurisdictions, to provide for reliable operation of the bulk power system. The term includes requirements for the operation of existing bulk power system facilities, including cybersecurity protection, and the design of planned additions or modifications to such facilities to the extent necessary to provide for reliable operation of the bulk power system. The term does not include any requirement to enlarge such facilities or to construct new transmission capacity or generation capacity.

Station Service Power: Small amounts of power needed to drive the ancillary equipment (e.g., motors, pumps, compressors, electronics) necessary to support the transition from the primary energy source (moving water, coal, oil, natural gas, and nuclear fuel) into electricity

Substation: Facility equipment that switches, changes, or regulates electric voltage.

Supervisory Control and Data Acquisition (SCADA): A system of remote control and telemetry used to monitor and control the transmission system

Synchronize: The process of bringing two electrical systems together by closing a circuit breaker at an interface point when the voltages and frequencies are properly aligned. When generators are brought online, they are said to be synchronized to the bulk power system

System Operator: An individual at a control center of a balancing authority, transmission operator, or reliability coordinator who operates or directs the operation of the bulk electric system in real time.

Tariff: A published volume of rate schedules and general terms and conditions under which a product or service will be supplied.

Transmission Operator: The entity responsible for the reliability of its "local" transmission system and that operates or directs the operation of the transmission facilities. The transmission operator is required to have a restoration plan, in accordance with Reliability Standard EOP-005-2

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1.0 Introduction

The power grid in the United States and most developed countries typically features a very high level of reliability of uninterrupted electricity service. Strict regulatory standards, rigorous operating and planning procedures, and proper engineering design ensure that the electricity grid is reliable and resilient against routine fluctuations in supply and demand, as well as against foreseeable failures of grid infrastructure components. During normal operating conditions, the majority of the power grid[2] remains energized. Generating units that are online but power down (known as spinning reserve) can be ramped up to provide power demand; and/or generating plants/units that are temporarily offline but are kept in standby mode, can be reconnected to the grid to meet power demand. The offline plants must draw relatively small amounts of power (station service power) needed to drive the ancillary equipment (e.g., motors, pumps, compressors, electronics) necessary to support start-up of the plant and begin the transition, via turbine-generators, from using primary energy sources (e.g., moving water, coal, oil, natural gas, nuclear fuel) to producing electricity.

Occasionally, though, rare events have impacted a large part of the electric power grid, resulting in a widespread shutdown of generating plants/units and de-energization of the transmission and distribution system. For example, on November 9, 1965, minor power fluctuations triggered automated controls to shut off electricity flow through a transmission line connecting northern New York State to the Canadian Province of Ontario. Within 20 minutes, 30 million customers in the region—15% of the total population of these two countries—found themselves without electrical service as a cascading series of automated protection actions plunged the local grids into darkness. Electrical power was not restored for up to 13 hours in some areas.[3,4]

Besides the direct impact on the customer loads served, blackout events are even more problematic because they make unavailable the station service power needed to conduct safe shutdowns of power plants to prevent damage to their turbine-generators, and then to restart and reconnect the power plants during grid restoration. Restarting power plant operation without any station power was in fact the primary challenge for many utilities during the 1965 blackout. According to the retrospective report released by the Federal Power Commission, "… little thought had been given in many instances to the idea that a generating plant on a large interconnected system would find itself without station power to shut down safely and re-start quickly…" That specific event, and the general lack of contingency planning for generator restart following blackout scenarios, led to the creation of additional safeguards to ensure that "… provisions have been planned or accomplished to insure a dependable source of emergency power for many stations which heretofore were dependent upon network connections."1 This provisioning came to be known as "black start."

While it is widely discussed in the context of grid reliability and resiliency, the provision of black start capability is not well documented in the public domain. This technical memorandum

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[2] Some plants may be offline for normal maintenance.

[3] *Prevention of Power Failures—An Analysis of Recommendations Pertaining to the Northeast Failure and the Reliability of the U.S. Power Systems, A Report to the President by the U.S. Federal Power Commission*, July 1967.

[4] The photograph of the Statue of Liberty with a blacked-out New York City in the background on the cover of this report is one of a series taken by Robert Yarnall Ritchie during the northeastern US blackout of 1965.

is intended to address that gap by providing a brief overview of the process of executing a black start (Section 2), discussing the technical requirements for black starting power plants and restoring grid operation (Section 3), and outlining the regulatory framework that drives the deployment of black start capabilities (Section 4). Not all generators are equally capable of, or desirable for, use in a black start capacity, and the key attributes of suitable black start plants are discussed in Section 3, along with desirable attributes of hydropower plants that make them most ideal for black start. Although the focus of this report is primarily technical, some economic issues are addressed in Section 5. An important step in the direction of disseminating information on this topic is also represented by the publication of the May 2018 Federal Energy Regulatory Commission (FERC) and National Electricity Reliability Council (NERC) report on black start resource availability, referenced and discussed in Section 5.2.

2.0 Black Start Process Fundamentals

Black start is the process of restarting operation of a power plant(s) from a completely unenergized operating state in order to power up other plants and loads to restore power to the electric power grid. Black start–capable plants/units provide the energy to jump start the electric system recovery, that is, to provide the first minimum amount of electric power that is required to power up the rest of the power grid (including other power plants and the transmission and distribution system).

Essentially, restoring an electric power system involves starting up a generating unit at a black start power plant, energizing the connected transmission and/or distribution lines, and powering nearby loads until the generating unit and the load stabilize. As soon as is practicable, a second generating unit at the black start plant is added to the electrical island to provide reserve capacity in case the first unit trips off. If the second unit does not have black start capability, it is restarted with station power from the grid—provided through the transmission or distribution lines energized by the first generating unit.

In a sequential restoration process, loads and generators are incrementally added to the electrical island, each time enlarging the electrical island in terms of generators and loads and reducing the size of the blacked-out region. This process continues until the entire grid is back in service. The power to start up a generating unit is sometimes referred to as "cranking power," much as a starter motor powered by the DC battery in an automobile "cranks" or turns the engine crankshaft, enabling internal combustion to start the engine. Based on the sizes, characteristics, and locations of the generating units and the topology of the transmission network, electric utilities plan the sequence for restarting generators. Power from generators brought back online is used to supply the necessary station power to bring other generators and loads online. (When overlaid on a transmission map, this sequence for restarting the grid is sometimes referred to as the "cranking path.")

If the blackout region is large, it can take a long time (e.g., hours to days) to restore generators and loads sequentially; in this case, parallel restoration is performed. In a parallel restoration, multiple geographically dispersed black start plants/units are powered up, and several electrical islands across the blackout region are simultaneously brought online. These islands grow as additional generation is brought online and load is restored. At some point, when these islands are large enough, they are connected to one another so that the electric grid once again becomes a single, stable interconnected grid network.

This report explores the process of executing a parallel black start from the perspectives of both the system operator and the black start power plant operator/owner. How a black start is implemented provides the context for identifying plant attributes that can expedite black start and grid restoration (further discussed in Section 3).

The speed at which the grid can be restored when black start is required depends upon both plant-specific characteristics and grid (power system) characteristics. These include the following:

- How much station power (or cranking power) a generating plant requires determines both (1) the magnitude of the on-site power resource needed to make the station black start–capable and (2) how much power the station requires from the grid if it is not black start–capable.

- Since larger-capacity generators can, once restarted, energize more of the grid, operationally is it preferable to energize the largest possible generators as soon as possible.

- Some generation technologies can be restarted and brought online sooner than others; quicker restarts result in faster grid restoration.

- Similarly, some generating plants require that other infrastructure be operational, and this may increase the time or power needed to restart. Two examples are (1) needing to pressurize a natural gas pipeline supplying a gas-fired plant; and (2) requiring that the system/plant operator can monitor and control the plant, i.e., requiring an operational supervisory control and data acquisition (SCADA) system.

- Since generators, once restarted, are used to supply station power to bring on additional generators, it is desirable to restart initially those generators that are strongly (more directly, with fewer transformers and switchgear in the path) connected electrically to many other generators (i.e., via functioning transmission lines).

- There are likely to be significant frequency excursions in the electrical islands in the early stages of restoration, and in the recovering system as a whole during the complete restoration process. Generators that can (1) withstand frequency deviations without tripping and/or (2) help stabilize system frequency and support voltage will expedite system recovery.[5]

- Geographic dispersion is important: operators try to expand the size of the electrical island(s) as much as possible to enable restoration of system loads throughout the grid.

Table 1 summarizes desirable blackout generator attributes for restoring the grid after a major blackout and whether they are location/topology specific (grid characteristics) and/or technology specific (power plant characteristics).

Table 1. Generator attributes for expediting black-start grid restoration.

Characteristic	Generation technology-dependent	Power system configuration-dependent
Minimal station power required for restart	●	
Minimal time needed to black start	●	
Large generator nameplate capacity	●	
Ability to withstand frequency deviations	●	
Ability to help stabilize system frequency and support system voltage	●	●
Minimal dependence on off-site infrastructure	●	●
Operating transmission connections to other generators		●
Geographic dispersal		●

[5] Koellner, Kris, Chris Anderson, and Roy Moxley, "Generator Black Start Validation Using Synchronized Phasor Measurement," SEL *Journal of Reliable Power*, 3(1), March 2012.

2.1 Black Start Sequence from a System Operator Perspective

Figures 1 through 9 illustrate, on a simplified hypothetical electric grid, a parallel restoration sequence from the perspective of the system operator.

Figure 1 illustrates an entire grid operating normally, with square symbols representing circuit breakers (red are energized; green are de-energized). Two load centers, North and South, are each served by two different generators. Two generators, Gen 1 and Gen 4, have been designated black start units. Transmission path Line 1–3 connects Gen 1 to Gen 3; transmission path Line 2–4 connects Gen 2 to Gen 4.

Black start planning begins long before the event requiring black start services. The planning requires

- Identification of critical loads, thorough power engineering analysis (see insert for an explanation of critical and priority loads)
- Identification of an optimal set of black start plants
- Identification of crank paths (the substations and lines that deliver the cranking power from the black start plant to the next power plants to be started), with each step (e.g., switching orders, power dispatch) ensuring the proper progression toward a safe and stable grid state

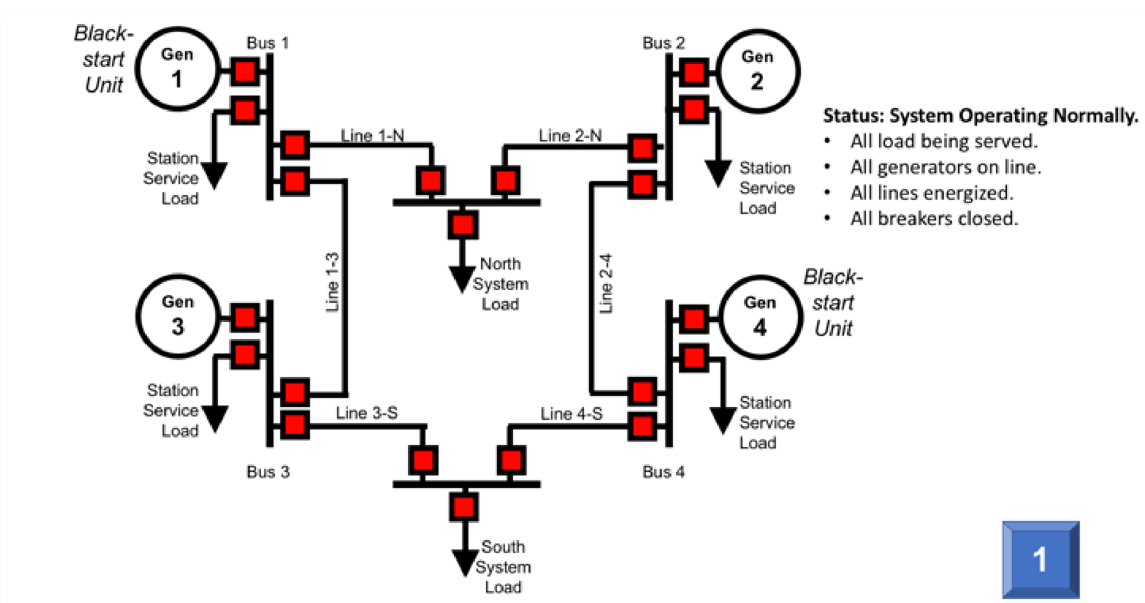


Figure 1. Electrical grid is operating normally.

Critical loads are loads essential to performing the restoration and sustaining the operation of the bulk power system.[1] Examples of critical loads include (in no particular order),

- Station service at transmission-level power control centers, transmission substations, and generating stations
- Gas pipeline compression stations
- Power system communication facilities
- Protective relays and schemes used to ensure public and personnel safety and to maintain the integrity of the electric grid
- Power transmission monitoring and control systems

Priority loads are important consumer loads that need to be restored promptly to mitigate the impact on public health and safety, the environment, or the economy. These include (in no particular order),

- Key military facilities
- Hospitals
- Water and wastewater treatment plants
- Telecommunication centers
- 911 dispatch centers
- Oil refineries
- Major financial centers

Figure 2 illustrates the condition of the grid immediately after a blackout event. Sensing a problem, all four generator breakers are opened (un-energized assets are shown in gray) by their protection systems. All other breakers are in an unknown state (yellow), so the topology of the system is unknown. At this point, transmission operators/owners and reliability coordinators communicate with one another to ascertain the condition of the grid, the precipitating event(s), and the extent of the damage.

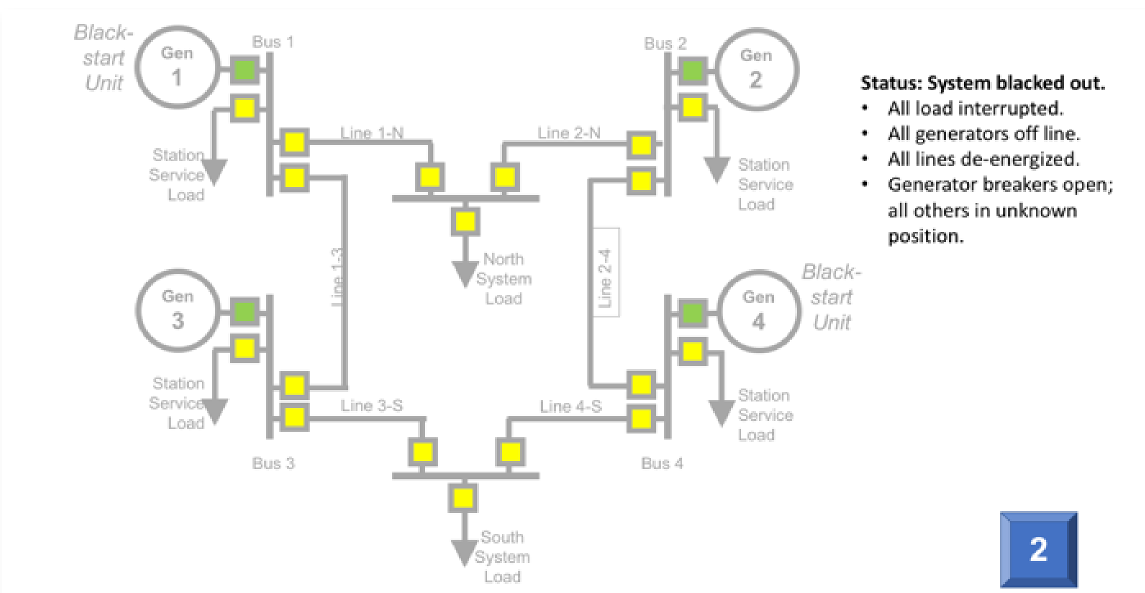


Figure 2. Grid is blacked out.

The assessment includes

- Geographic extent, that is, the boundary of the blackout area (physical view) and the electrical circuits affected (electrical view)
- Impact on load served[6] with emphasis on understanding the impact on *critical* and *priority* loads
- Impact on generation facilities with emphasis on understanding the impact on black start plants and cranking paths
- Impact on all other substations, lines, and structures
- Impact on supporting infrastructures (e.g., natural gas, telecommunications, rail transportation, roads, and bridges)
- General understanding of the precipitating event (the event that caused the blackout) and the extent of damage to customer facilities and loads

After the condition of the grid, loads, and generating stations is ascertained (Figure 3), planning for service restoration begins. If the outage is extensive (as any outage requiring black start resources would be), emergency operations centers will be convened to manage restoration of the bulk power system, and will be staffed to

- Manage the restoration operations (including coordinating with other emergency operations centers)
- Manage external communications
- Perform operational engineering studies
- Manage repair and refurbishment activities

In each involved electric utility company, one person will likely be responsible for the company's activities in the overall restoration process. This person will coordinate the activities of the company's entire restoration team.

[6] Based on NERC "Severe Impact Resilience Task Force Considerations and Recommendations," May 2012.

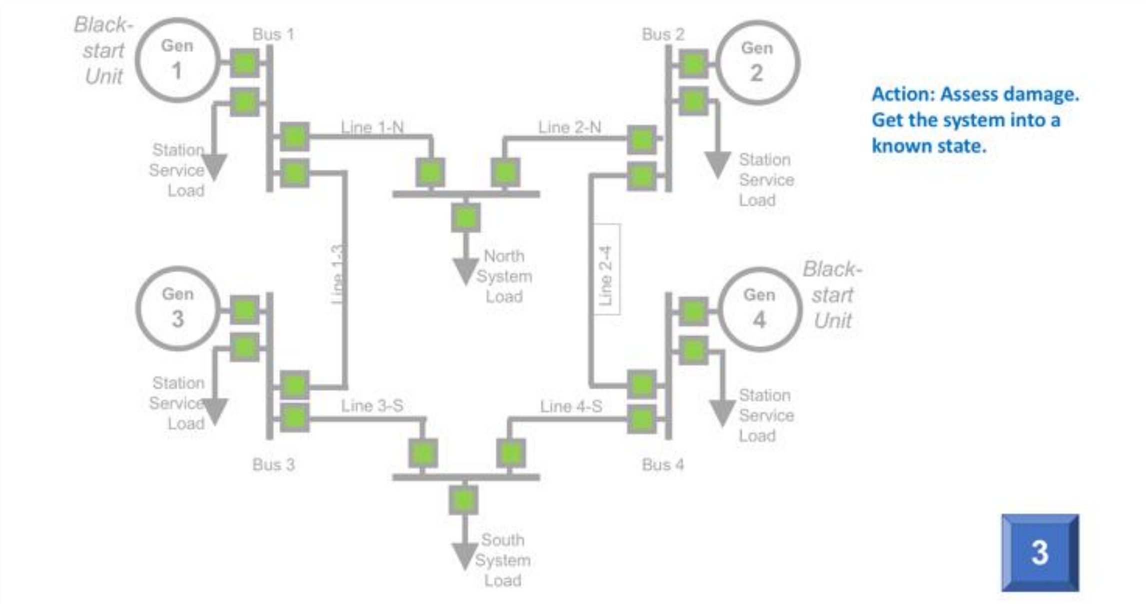


Figure 3. Grid is still blacked out but in a known state.

An operations team will be responsible for the work in the field, typically focusing on

- Establishing and maintaining situational awareness, that is, keeping apprised of the status of generating stations, work orders, weather conditions (current and forecast), gas and other resource supplies, telecommunications systems, necessary transportation infrastructure (e.g., roads, bridges, railroads, and barge facilities), and other critical infrastructures
- Organizing restoration efforts into implementable work orders
- Coordinating activities with other utility company responders
- Dispatching crews to implement work orders
- Monitoring progress of restoration efforts inside and outside the company

A communication specialist will be responsible for providing status updates and general (nontechnical) communication with utility customers and other stakeholders (of which there can be many). For instance, the electrical generation in a hydropower plant affects upstream and downstream flows and water levels which, in turn, impact irrigation, fishing (because of oxygen levels), waterway navigation minimum levels, and large nuclear or fossil power plant operation (because of cooling water requirements). The communication specialist will also be responsible for coordinating with law enforcement, major industrial facilities affected by the blackout, and the news media. During a black start and grid restoration event, the activities become important to a large number of people and receive attention and oversight from many different quarters.

A team of operational engineers will ingest technical information from other entities and perform studies on proposed remediation activities. The team will

- Analyze all planned activities to ensure that every step in every switching order will transition the electric grid to a safe and stable operating state
- Analyze all completed activities to confirm the electric grid is behaving as expected and to establish a new operating baseline for future analysis
- Identify spares and noncritical operational equipment (equipment in service) that might be removed from service to be used to replace damaged critical equipment (i.e., cannibalized). This option is sometimes exercised if replacements for damaged critical equipment are unavailable in the required timeframe.

One or two people will likely coordinate procurement activities; they will

- Identify materials and equipment needed for restoration, with emphasis on long-lead-time equipment
- Manage the supply chain (e.g., place orders, arrange for delivery, and track status of orders)
- Manage calls to action via mutual support agreements with other utilities while maintaining awareness of the terms and conditions of each contract
- Manage relocation of heavy equipment and transportation of assets from warehouses to work sites

The operational status of the SCADA and telecommunication systems will be carefully evaluated. If the status of the SCADA system is questionable, personnel (e.g., linemen, electricians, operators) may be dispatched to staff transmission substations critical to the restoration. For example, these staff members would read gauges at the substation and relay the readings (manually taken from the local panels) to the control center. Staff would also operate equipment (e.g., open or close circuit breakers) at the direction of the control center.

Note that, because the situation is usually fluid and uncertain, the restoration plan is continually modified as the work progresses, based on the extent of work completed (in-house and neighboring systems), the operational state of the electric grid, current and predicted weather conditions, and other factors.

After the situation on the grid is evaluated, and it is established that there are paths that can be safely re-energized, black start units are called to service (Figure 4). They begin by powering their own station service loads. This begins the delicate, sequential process of balancing output from generators with an increasing load.

The next step could be either to energize the crank path and bring more generation online, or to begin energizing the main system loads. The decision would be based on the characteristics of the black start generators (e.g., minimum station power needed, power plant generation capacity, large ramp rate capability).[7]

[7] At this point, the flexibility inherent in the operation of hydropower plants becomes especially useful.

Balancing generation and load is critical. However, in some cases, loads that are energized after being offline for an extended period may draw up to ten times their normal operating (steady state) level for a few seconds (this is known as “inrush current”) and then continue drawing less current but still more than their steady state level for about 30 minutes (see “cold load pickup” insert). Especially at the beginning of a power grid restoration, the inrush current can cause significant frequency excursions if the level of generation cannot keep up with the changing load; it might black out the system again and require the black start process to begin anew.

Generating units with the following three key aspects of operational flexibility are especially valuable in the early stages of repowering the grid after a black start:

- Ability to operate within a wide range of operating frequencies (not an ideal condition, and allowed not for a long time, but long enough to stabilize an island)
- Ability to operate over a wide range of output power
- Ability to change their power output rapidly by ramping power up or down quickly, known as a fast ramp rate, with the most flexible plants able to reach full power in under 1 minute

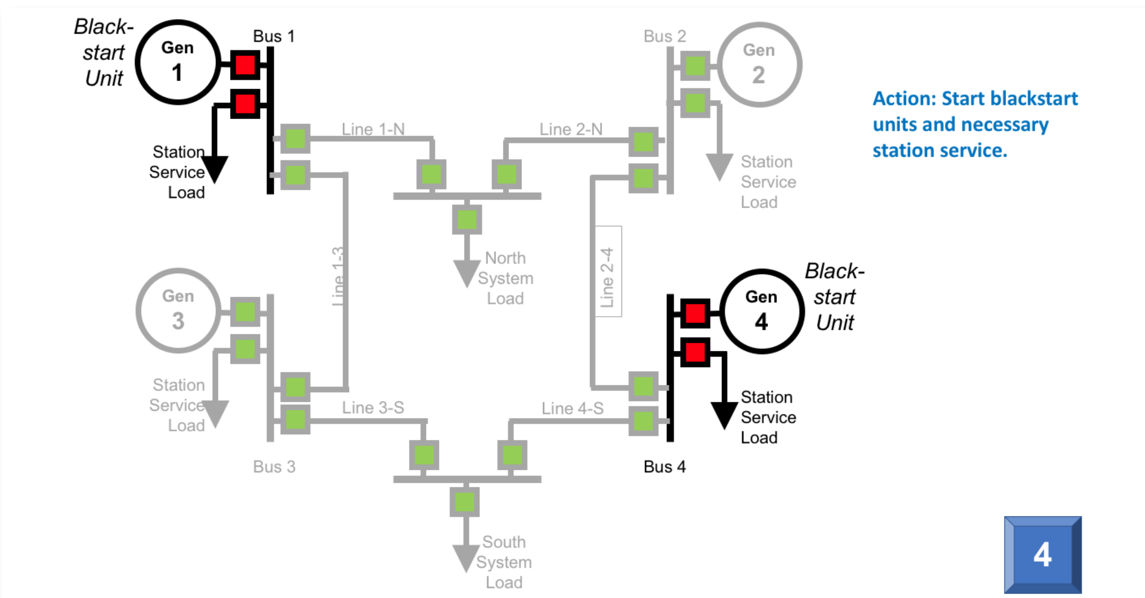


Figure 4. Black start units are started.

Cold load pickup is the process of energizing load centers that have been offline for an extended period. During this process, loads draw up to ten times their normal levels for 2 to 4 seconds and then draw up to twice their normal levels until they recede to normal levels, about 30 minutes later. Two phenomena drive this process: *loss of load diversity* and the *inrush current* of electric motors.

In a steady state, air-conditioning, heating, pumping, and other intermittent loads cycle off and on independent of one another (in a random manner as seen from the feeder). When power has been out for an extended period, this *load diversity is lost* as all loads resume operation at the same time.

The other phenomenon is the *inrush current* needed by electric motors. When first started, electric motors draw about ten times their normal level, decaying to normal as the motor approaches operating speed. When a feeder is energized after an extended outage, all motors start at the same time and draw inrush current simultaneously.

Once any damage to the transmission assets is remediated and substations are staffed with trained personnel (as needed), crank paths are energized (Figure 5). Switching actions (i.e., the opening and closing of switches, circuit breakers and other switchgear) are analyzed by operational engineers to make sure that, as the topology changes with every switching action, the system is transitioning to a safe and stable operating state.

Loads are selectively added at a pace that closely maintains the generation-to load-match and thus sufficient stability of the system frequency and voltage to prevent reenergized generators from tripping off. The speed at which load can be restored and/or additional generators can be supplied with station power for restart is constrained by the operating generator ramp rates —the speed at which their power output can be increased (Figure 6). The same challenges to balancing generation and load posed by the cold load pickup phenomenon discussed in relation to Figure 4, applies here.

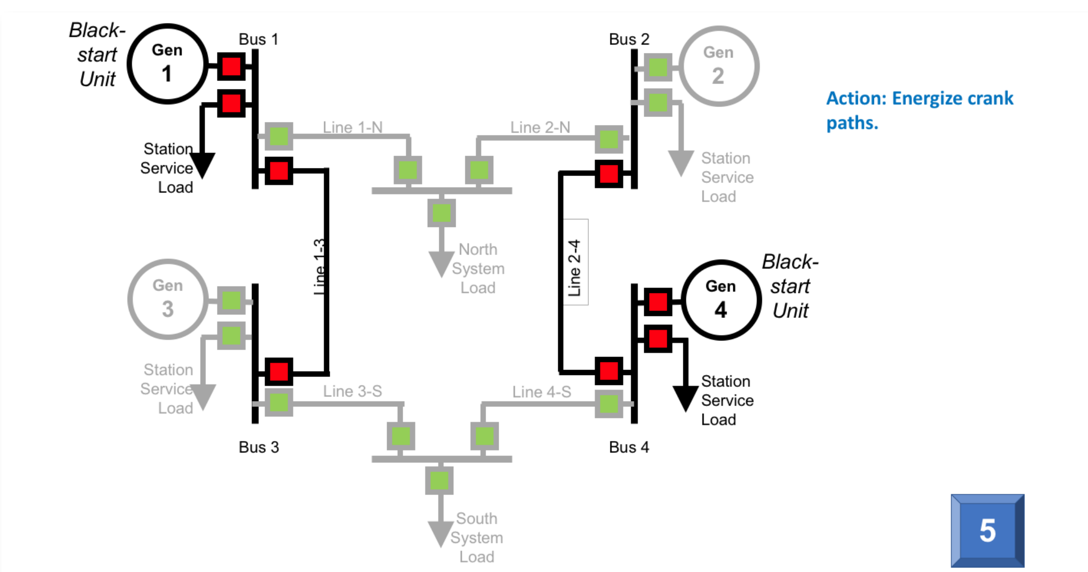


Figure 5. Crank paths are energized.

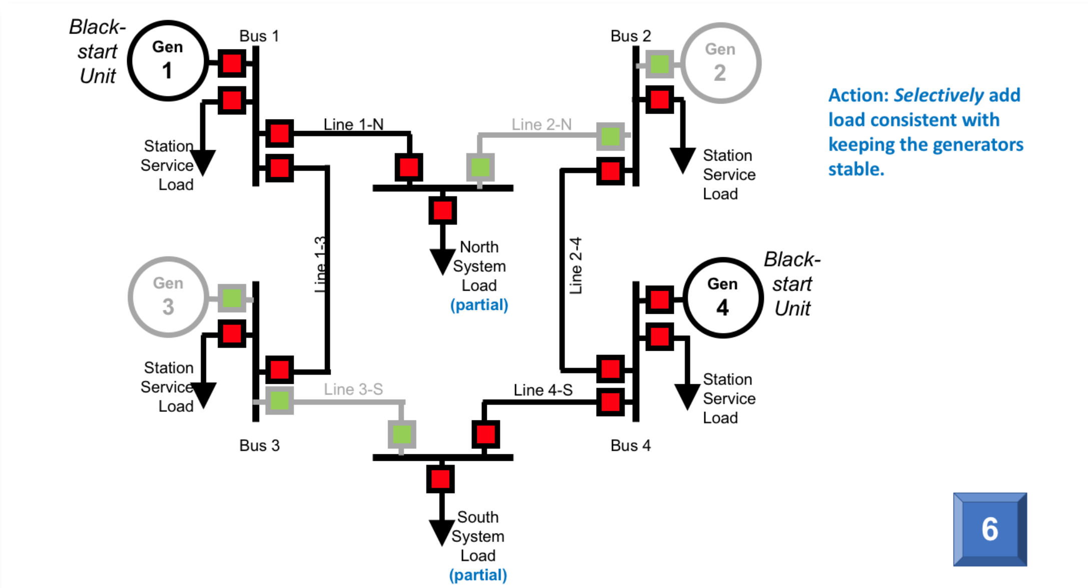


Figure 6. Loads begin to be restored.

In the next phase of restoration, target generators (not black start units) begin to be restored, consistent with their operating limits (Figure 7). Generating facilities (i.e., conventional or pumped storage hydropower [PSH], fossil, nuclear, and gas turbines) require electricity to power a variety of auxiliary equipment needed to operate the plant. Most conventional generators require electricity to first create the magnetic field needed for their operation, that is to convert the *kinetic energy* in the prime mover (e.g., the energy in flowing water, steam from boilers) to *electrical energy*. In other words, initiating electricity production requires electricity, and how much is needed to initiate production depends on the specific generating technology and design/characteristics of the power plant.

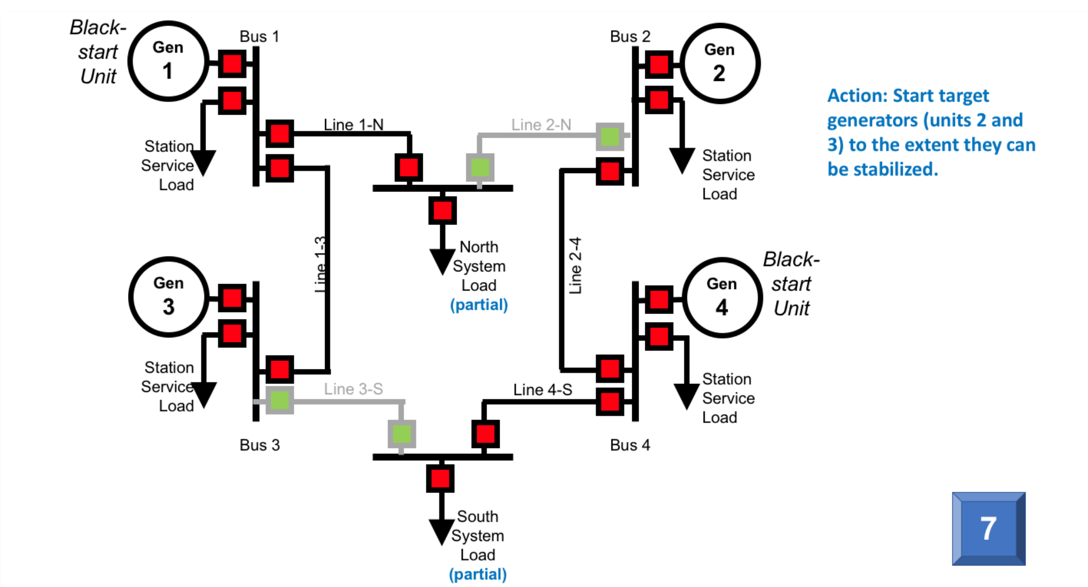


Figure 7. Target generators begin to be restored.

Table 2 shows the approximate amount (as a percentage of nameplate capacity) of station power that must be provided to re-energize some types of power plants. The order of re-energizing power plants affects how much and how soon load and other generators can be restored. Larger-capacity power plants, once restarted, can provide more power to restore other generators and loads; but they usually require more station power (either drawing more power from the recovering grid or requiring more black start resources on-site) than smaller generators. There is a trade-off regarding larger power plants: their advantage is that, once restarted, they can expedite restoration of other plants; their disadvantage is that they require more grid power (or black start capability) to be restarted. In the early period of grid recovery, as operating generators are brought online and operate to match load (either reconnected loads or station power for offline generators), the system frequency will not be as stable as during normal operation (i.e., it can oscillate much higher or lower than the standard operating limits for normal 60Hz frequency).

Table 2. Power required to energize a power plant from a cold start as a percentage of its generator capacity.[8]

Generator type	Typical start-up power required (% of nameplate capacity)
Nuclear	7 to 8
Thermal	7 to 8
Gas turbine	1.5 to 2
Hydroelectric	0.5 to 1

Prioritizing the generators to be restarted next (or deciding which ones should be provided with black start capability) is based on

- The amount of generation and load (and their balance) on the electrical island
- The amount of station power or black start resources required to restart a plant (Table 2)
- The plant's maximum capacity
- The plant's available transmission connections to other plants (including connections that are out of service and could be energized by the target plant and connections that are in service and capable of supplying station service to restart the target plant or its non–black start generators)
- The plant's minimum operating load level and its ramp rate for changing output level
- The plant's ability to operate (without tripping) during frequency excursions[9]

[8] *Performance of a Hydro Power Plant During Black Start and Islanded Operation*, S. R. Kurup et al., National Institute of Technology Calicut, Kerala, India, 2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES).
[9] Koellner, Kris, Chris Anderson, and Roy Moxley, "Generator Black Start Validation Using Synchronized Phasor Measurement," SEL *Journal of Reliable Power*, 3(1), March 2012.

- The plant's ability to stabilize the grid's frequency and voltage (including its ramp rate, inertia, and tolerance of frequency excursions)[10]

In a parallel restoration process, once two adjacent electrical islands are up and operating in a stable condition, a synchronization process (i.e., to match voltages, angles, and frequencies at the connection points) is initiated before reconnection is carried out (Figure 8). Under the direction of the transmission operator, each electrical island is brought to the same frequency and voltage magnitude and angle. When all three parameters are within the required tolerance for reconnection, one of the interconnecting paths (Line 2-N or Line 3-S in Figure 8) is energized, effectively restoring the grid to a single interconnection (Figure 9). After that, the remaining open line is energized, bringing redundancy (i.e., multiple transmission paths and generation) to the interconnection.

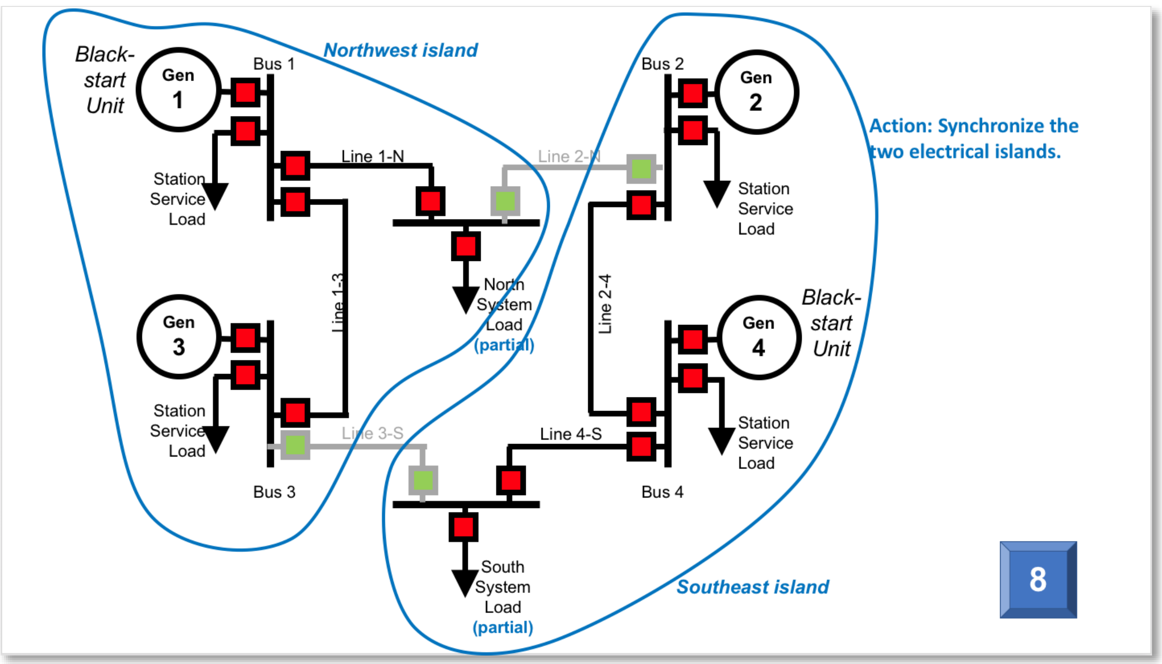


Figure 8. Electrical islands prepare for synchronization.

[10] *Ibid.*

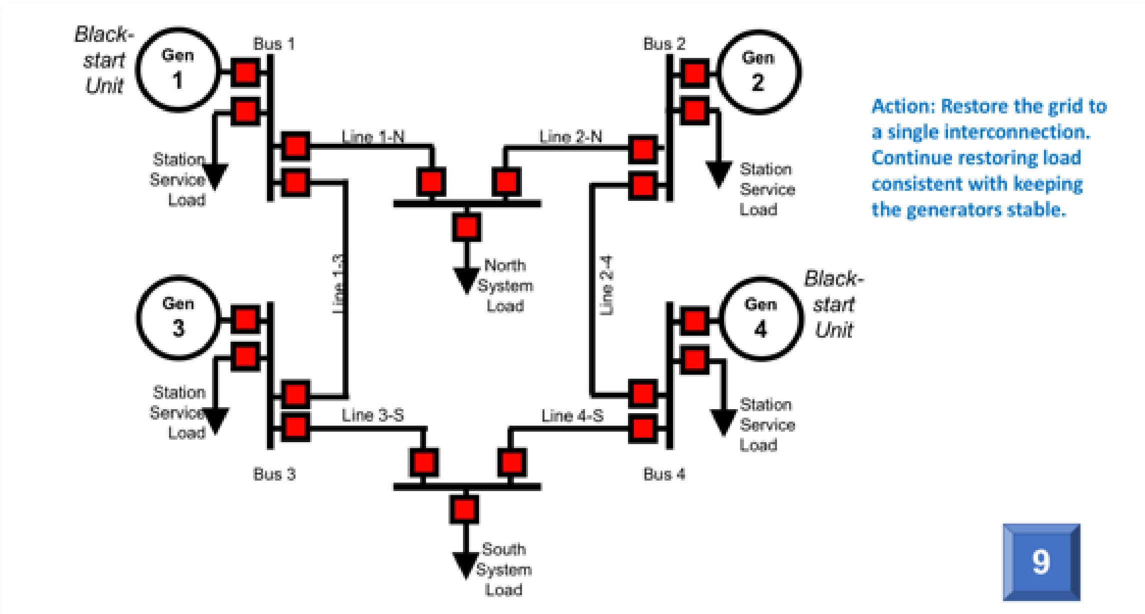


Figure 9. Grid is restored to a single interconnection.

This process is completed if there are more islands. Once that is finished, the restoration of the grid is complete. Next, the duties and authorities temporarily delegated revert back to their normal assignments. Now the detailed analysis of the failure event and restoration begins.

2.2 Black Start Sequence from a Plant Operator Perspective

During a blackout scenario, typically, every electric utility and generating facility in the affected area conducts its own assessment of the situation and plans its own response to the coordination calls from the system operator. Upon onset of a major system interruption, black start plants immediately assess their ability to respond; that includes ensuring that required staff are available, reviewing pre-established switching orders and other black start procedures, assessing the readiness of plant equipment (generating and auxiliary systems, fuels and other consumables), and reviewing the restoration protocols agreed to with the system operator. Figures 10 through 17 illustrate a black start call to action from the perspective of the plant operator.

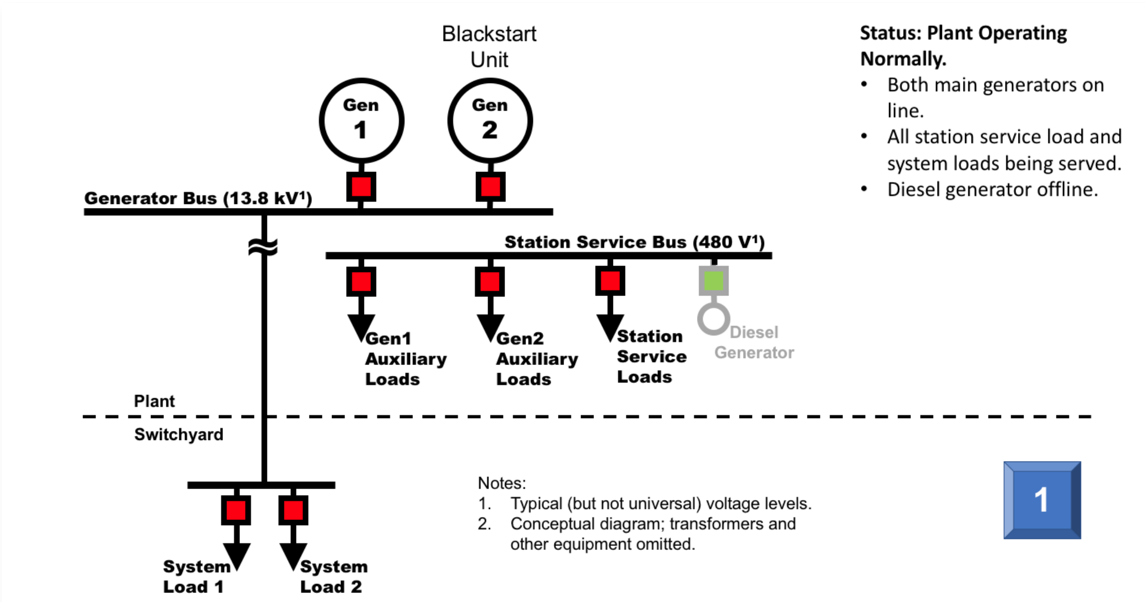


Figure 10. Plant is operating normally.

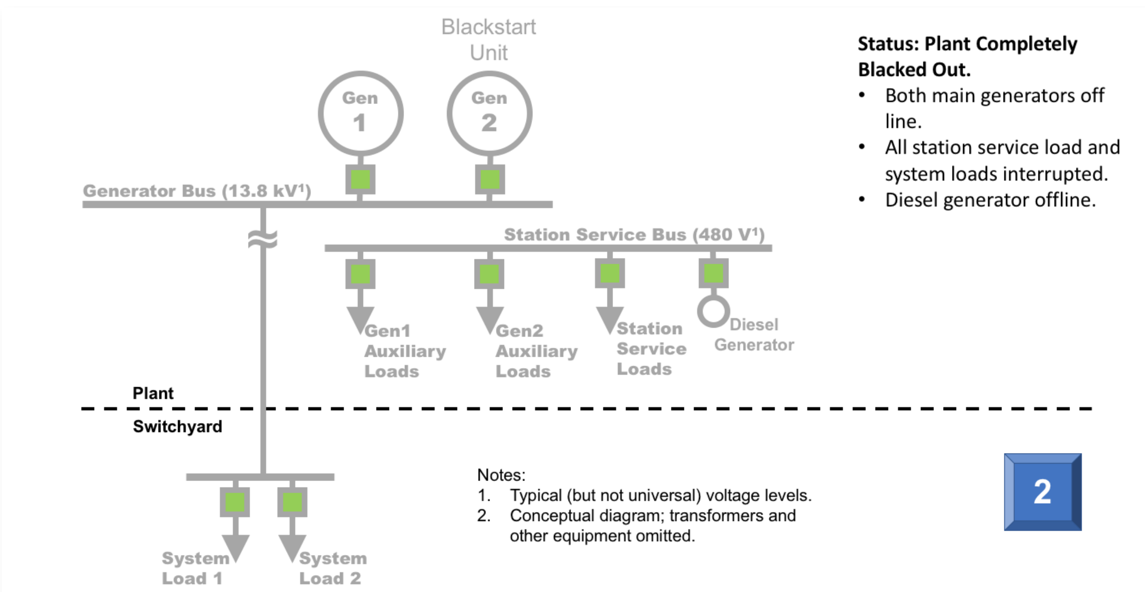


Figure 11. Plant is completely blacked out.

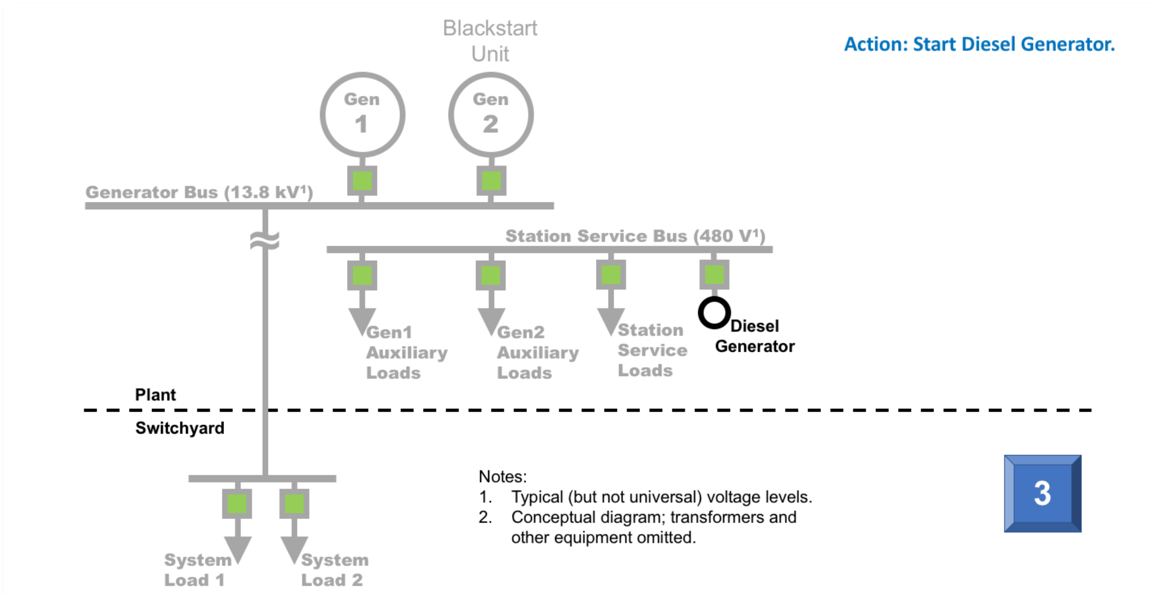


Figure 12. Emergency diesel generator is started.

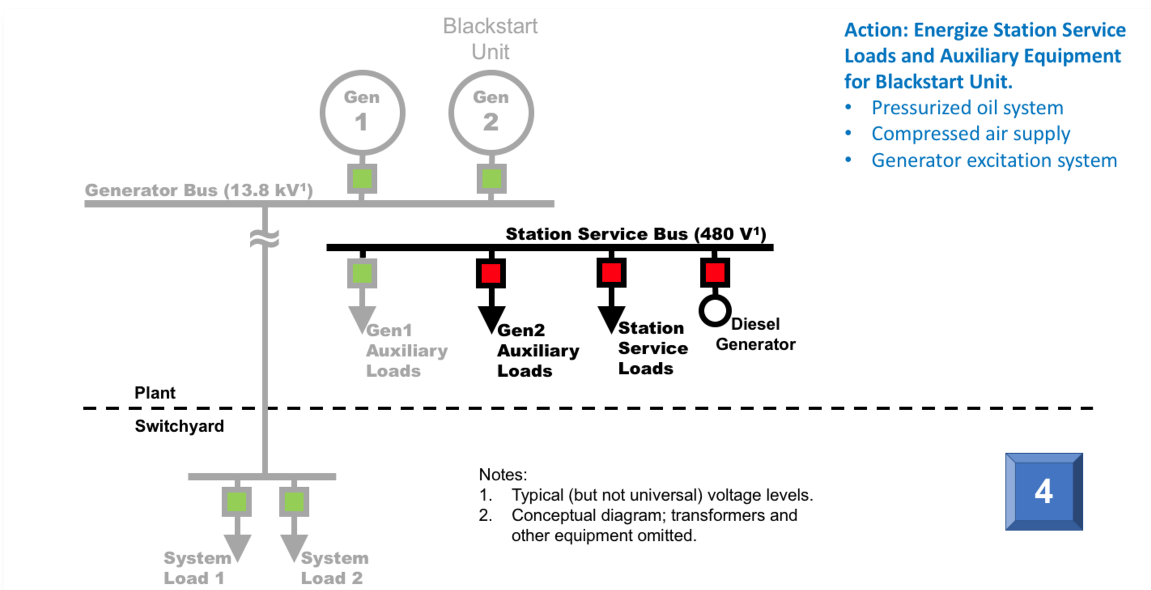


Figure 13. House loads and auxiliary loads for black start unit are energized.

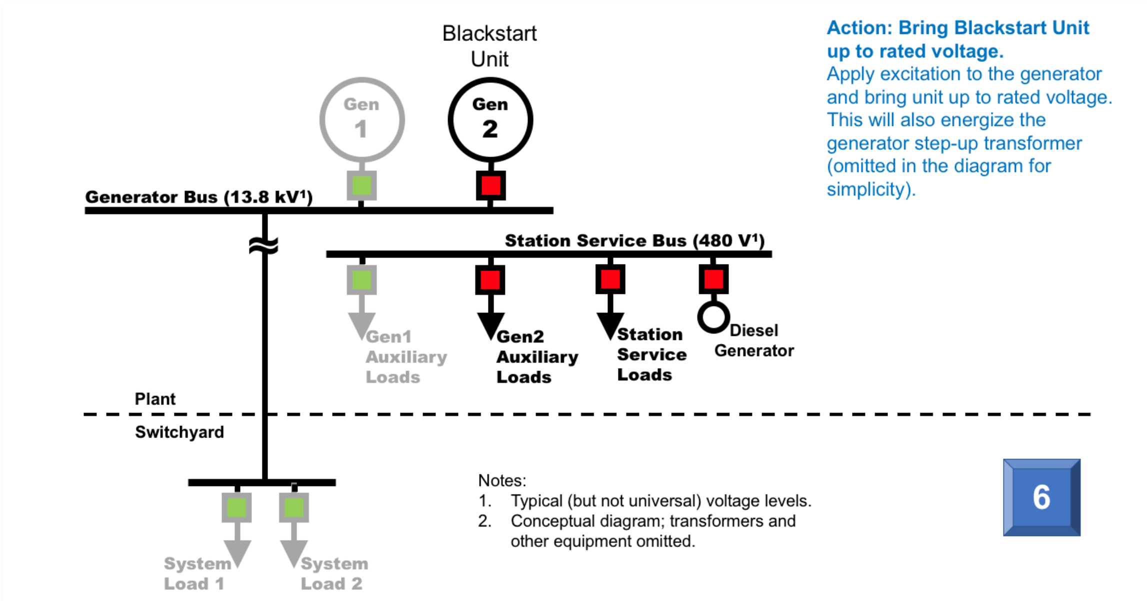


Figure 14. Black start unit is brought up to speed.

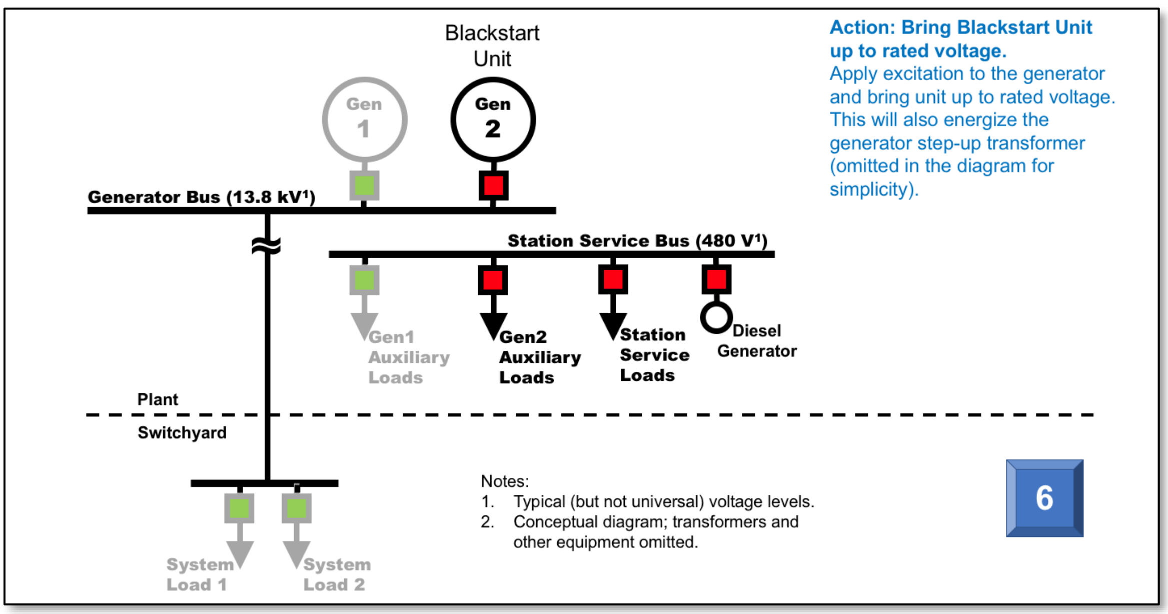


Figure 15. Black start unit is brought up to rated voltage.

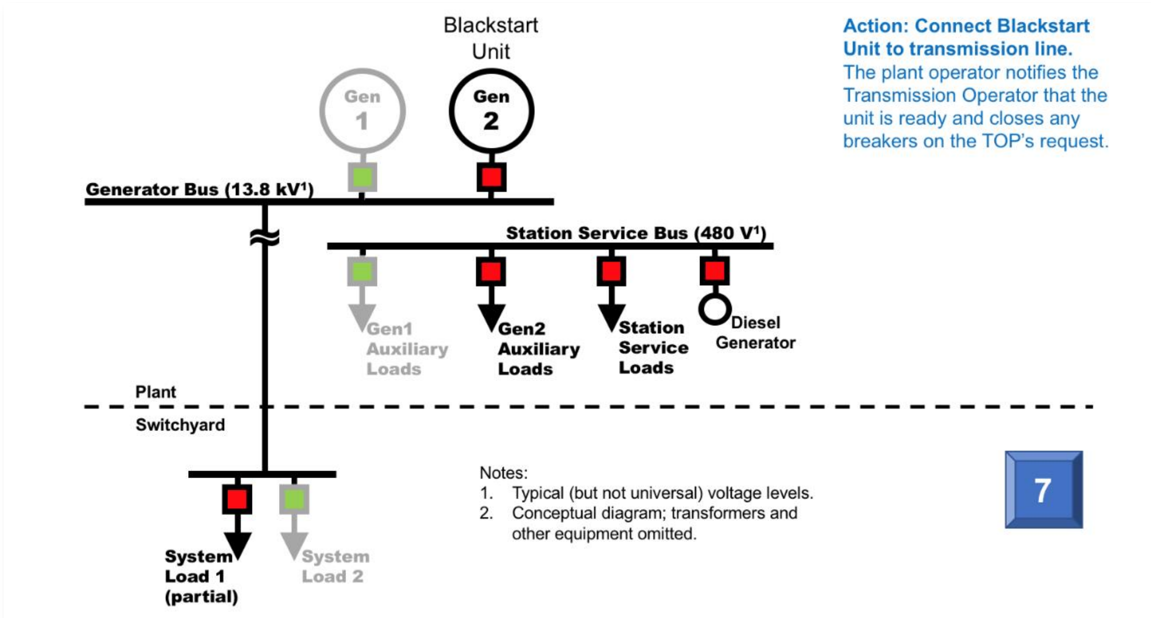


Figure 16. Black start unit is connected to transmission system.

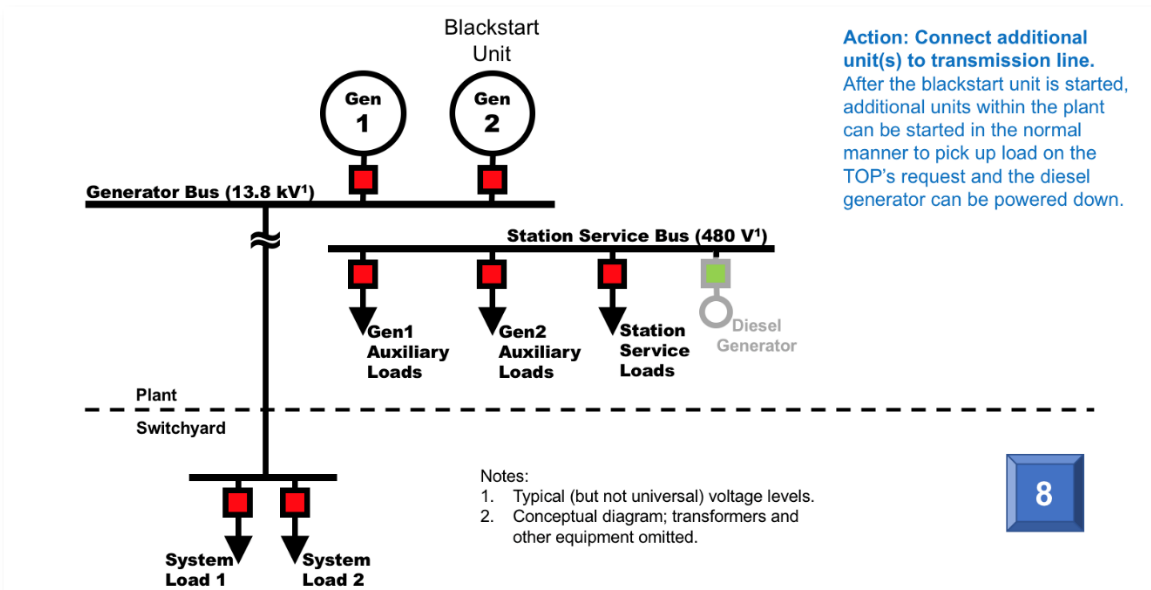


Figure 17. Additional units are started and connected to transmission system. Plant resumes normal operation.

3.0 Black Start Technical Requirements

Provisioning black start resources for restoring electric service involves several considerations:

- The station power required to reenergize the plant (also balanced against the output—nameplate capacity—of the plant when it is in operation)
- The electrical configuration of the power plant (internal considerations such as the real and reactive power generating capacity of the black start unit, buswork and circuit breaker configurations, location of the emergency generator with respect to the black start unit, and other considerations)
- The ramp rate, ability of the plant to rapidly vary its power operating point, which gives flexibility to the dispatcher as the recovering grid is stabilizing
- Frequency sensitivity—can the plant tolerate frequency excursions and/or can its inertia (the larger the generator capacity, the greater the inertia) or rapid power output response help stabilize system frequency?
- The topology of the electric transmission system (external considerations in terms of electric connections to other generation and load)
- Operational support
  - Telecommunication systems for communicating with the transmission operator/owner
  - Written processes, agreements, operating procedures, and plant staff training

Each of these considerations is discussed in the sections that follow. Table 3 compares both plant-centric and topological characteristics of conventional power plant types that are feasible for use in a black start scenario (nuclear, solar, wind and battery storage systems are not currently used for black start but will be discussed later).

Table 3. Plant-centric and topological characteristics of resources feasible for black start.

	Hydro (conventional; large units)	Hydro (pumped storage)	Combustion turbine	Combined cycle	Coal or other fossil fuel (thermal)
Go/no-go requirements					
Able to start without an outside electrical supply (fundamental requirement)	Yes (if so equipped).	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Sufficient real power capability	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Sufficient reactive power capability	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)	Yes (if so equipped)
Required attributes					
Short starting time (less is better)	Sub-hour	Sub-hour	Sub-hour	Hours	Many hours
Number of units at black start facility	Many units typical at larger plants	Usually several units	Usually several units	Usually several units	Often more than one unit

Table 3. Plant-centric and topological characteristics of resources feasible for black start (continued).

	Hydro (conventional; large units)	**Hydro (pumped storage)**	**Combustion turbine**	**Combined cycle**	**Coal or other fossil fuel (thermal)**
On-site fuel inventory of black start fuel	Ample fuel (water) nearly always available unless impacted by drought conditions	Fuel (water) would need to be held in reserve for black start purposes	Fuel available if pipeline remains in service and pressurized	Fuel available if pipeline remains in service and pressurized	Fuel (local coal pile) nearly always available but must be pulverized
Complexity of necessary auxiliary systems (e.g., fuel supply, cooling, emission controls)	Very simple	Very simple	Simple	Somewhat complex thermal systems	Very large and complex thermal systems
Tolerance of (or amelioration of) frequency excursions	Yes	Yes[11]	If equipped, can tolerate excursions, but has little inertia	Depends on plant characteristics and controls	Large inertia but cannot ride through frequency excursions
Ramp rate/load following (higher response rate is better)	Responsive within turbine settings	Responsive within turbine settings	Responsive	Moderate ramp rates	Moderate ramp rates
Cranking path switching (less is better)	Location dependent (i.e., not related to type of plant). Less dependence on switching in transmission substations—usually by minimizing paths through transmission substations—is more favorable				
Number of target generation facilities (more is better)	Location dependent (i.e., not related to type of plant). A black start plant capable of cranking two or more target generating plants is more favorable than a black start plant capable of cranking only one. Many phenomena can cause a major power outage, so flexibility in restoration plans is of high value				
Number of independent cranking paths to target generation facilities (more is better)	Location dependent (i.e., not related to type of plant). A black start plant that can reach its target generating facility/facilities via two or more cranking paths is more favorable than a black start plant that depends on a single path. Flexibility in restoration plans is of high value				
Number of transmission transformers in the restoration zone (less is better)	Location dependent (i.e., not related to type of plant). Like electric motors, large power transformers draw significantly higher current when first energized—up to ten times the normal values for up to 1 minute. Switching procedures and settings on protective relays need to account for this. The fewer transmission transformers in the restoration zone, the simpler the switching procedures can be—and simplicity in restoration plans is of high value				
Off-site power source for nuclear power plant	Location dependent (i.e., not related to type of plant). US nuclear power plants require that a plant (and associated transmission paths) be designated as a source of offsite power to keep safety systems operational in the event power is lost inside the plant. Other units at plants designated to provide off-site power to nuclear plants can likely be leveraged to provide black start service				
Telecommunication systems to coordinate restoration activities with the transmission operator	Not driven by fuel type. Black start plants need to be equipped with voice and data systems capable of operating during blackout conditions. Plants with ample primary and secondary communication systems are favorable. Plants with tertiary communications systems are even more favorable				
Comments	Commonly used for a black start. Also, commonly used as a source of emergency off-site power for nuclear power plants	Not commonly used for a black start although it is technically possible to equip the plant to do so	Commonly used. Electricity is commonly (but not exclusively) used at compression stations to maintain gas pipeline pressure. Combustion turbine availability depends on gas pipeline being unaffected by the power outage	Not common but not rare. Electricity is commonly (but not exclusively) used at compression stations to maintain gas pipeline pressure. Combined cycle availability depends on gas pipeline being unaffected by the power outage	Not commonly used. Significant station service load for fuel handling (conveyors, pulverizers) and forced draft equipment (fans). Significant complexity

Legend: Favorable. | Somewhat favorable | Not favorable | Location dependent, or not driven by fuel type

[11] *Michigan Public Service Commission, Report on August 14th Blackout*, November 2003.

3.1 Plant-Centric Characteristics

For generating stations, the fundamental requirement for providing black start service is the ability to start operations from a completely shut down (fully de-energized) state without access to outside power. Since, at any one time, a power generating unit may happen be out of service for planned maintenance or a forced outage, power plants with several generating units capable of self-starting are more valuable than plants with only a single unit.

A qualitative comparison of different generation technologies from the perspective of suitability for black start operations is provided in Table 3, and, in more general terms, generator-centric requirements can be summarized as follows:

- Ability to start without an outside electrical supply (i.e., outside the power plant itself). This is fundamental: black start plants are the initiating points of restarting (bootstrapping) the electric grid from a completely de-energized state.

- Short starting time. The faster a black start generator unit can be restarted and brought back online, the faster the target power plant can be restored. In a power plant, once one unit is started, others can be brought back online as deemed necessary by the transmission operator. The goal is not to simultaneously start every unit quickly, but to be able to quickly call to action the right amount of generation as each increment of load is restored.

- Output variability/ramp rate and tolerance of frequency excursions. The flexibility of a plant to quickly vary its power output to match changing power system demands in the early stages of grid restoration provides more flexibility to the system dispatcher as new loads and generators are brought online. Sensitivity to frequency deviations is also a related characteristic: how well does the plant tolerate frequency excursions with regard to continuing to operate, and/or does its inertia or rapid output response help stabilize system frequency?

- Sufficient real power capability. The generating unit needs enough real power capability to power up other generator (i.e., their exciters, auxiliary equipment, and station service loads), in addition to its own exciter, auxiliary equipment and station service loads. For hydropower plants, this may include the power necessary to operate the intake gates.

- Sufficient reactive power capability. The generating unit needs enough reactive power capability to supply the transmission line charging current and to feed the inrush currents of large power transformers as they are restarted.

- Number of black start–capable units at the black start power plant (more is better). The more units at the plant capable of self-starting, the more likely it is that one will not be unavailable because of routine maintenance or a forced outage.

- On-site fuel inventory of black start fuel (more is better). Generally, a half-day's worth of fuel is the minimum; 3 to 4 days' worth is preferable (calculated for running at 50% output). For hydropower generating facilities, this translates into having fuel to power the diesel generators and an adequate supply of water in the upper reservoir or from forecast inflows.[12] For gas turbines and combined cycle units, this translates into diesel fuel needed to start the cooling system and pressurize the natural gas pipeline. For coal units, this includes similar diesel fuel requirements (for cooling water pumping and fuel handling machinery) plus an initial supply of pulverized coal.

In general, the way these characteristics (e.g., starting time, fuel security) translate into formal technical requirements for black start power plants varies with the specific service territory and electricity market area. Examples of how these differences may play roles in different restoration plans, or in regional transmission organization (RTO)/independent system operator (ISO) manuals, are shown in Table 4.

Table 4. Technical requirements of restoration plans among different regional transmission organizations/independent system operators.

	Starting time	Fuel inventory (run time)
PJM	3 h.; 4 h. (off-site power to nuclear station)	>16 h or as specified in restoration plan
CAISO	10 min	>12 h or as specified in black start agreement
ERCOT[13]	6 h	72 h (preferred)
ISONE	Not mentioned, but needs to be less than the date stated in the application	>2 h (alternative energy resource, including hydro); >12 h (other)
NYISO (Con Ed)	90 min (gas turbine); 8 h (steam turbine)	Not mentioned
MISO (ATC)	1 h	8–96 h (50% rated output)

PJM = Pennsylvania, Jersey, and Maryland; CAISO = California ISO, ERCOT = Electric Reliability Council of Texas; ISONE = ISO New England; NYISO = New York ISO; MISO = Midcontinent ISO.

The validation of black start capability during testing events may provide some specific technical requirements that lead to differences in how the various generating technologies can be applied for black start restoration. For instance, according to ISO New England (ISONE),[14] "alternative energy resources, including hydropower resources, must run at full capacity during a shutdown of the transmission system for at least 2 hours to qualify as a black start resource. As a further example, requirements in the Con Ed region of New York Independent System Operator (NYISO)[15] dictate that gas turbines synchronize and operate at minimum load within 90 minutes; the requirements for steam turbines extends this window to 8 hours, as the two technologies have very different start-up and ancillary equipment specifications. CAISO has uniquely strict requirements: black start units must be able to start with a dead primary and station service bus

[12] The presence of multiple fuel sources in black start plants is a favorable characteristic. Increased attention is being given to plants dependent on a single fuel; in today's market, this is typically dependence on natural gas pipelines. Increasingly, these gas plants are being equipped to be able to run on oil (stored on-site).
[13] 2018–2019 Black Start Service Request for Proposal, Electric Reliability Council of Texas.
[14] *ISO New England Operating Procedure No.11 Blackstart Resource Administration*, rev. 9.1, August 31, 2018.
[15] *NYISO System Restoration Manual*, New York Independent System Operator, version 4.3, July 2010.

within 10 minutes.[16] Notably, over 80% of all hydropower capacity in the United States can reach full power from cold start within 10 minutes.[17]

3.2 Grid Topology Characteristics

Technical considerations for black start planning related to conditions external to a particular plant include the electrical distance to the target generators and the transmission network topology (i.e., connections to neighboring power plants and loads, number of connections, switchgear and transformers in the electric paths). A high degree of operational flexibility is of high value because the specific conditions and needs of a black start scenario are difficult to predict. These external, i.e., not plant-specific, technical considerations can be summarized as follows.

- Cranking path switching (less is better). Switching actions (opening and closing of switchgear) drive the topology of the transmission system, determining where power can and cannot flow. Switching high-voltage transmission assets requires analysis to ensure that the bulk power system is being switched into a safe and stable configuration. Switching errors may cause destructive transients (i.e., high current levels) that lead to equipment damage (due to currents higher than the equipment is designed for) and loss of human life (e.g., as a result of a fault from the transient or equipment exploding). The fewer switching actions required of the transmission operator to isolate/clear the cranking path, the more quickly the cranking path can be established. A direct path (i.e., few switching operations with few transformers) is the best.

- Target generators in reach (more is better) of the black start generator. Balancing generation and load is a complex process, even during normal operating conditions. During service restoration, transmission and generation assets are operated in modes that can be very different from typical. Thus flexibility on the generation side represents a key benefit. For instance, the possibility of selecting units from a number of different plants, each one with unique electrical characteristics, to perform the various steps in the restoration process will facilitate and speed up a full recovery. It also mitigates the risk related to the possibility that any one of the selected plants is unavailable for restart because of an outage (forced or planned).

- Cranking path redundancy (more is better). In planning for an unknown event, having multiple transmission line paths by which a black start plant can reach target generator(s) mitigates the risk that the unavailability of any specific path—e.g., because of damage from the event that caused the outage—will hinder the return to service of the target generator. A black start generator with multiple paths to its target(s) is, of course, most desirable.

- Number of transmission transformers in the relevant area (fewer is better). Transformers require inrush current when powering up from an unenergized state. Therefore generators

[16] *California Independent System Operator Corporation Fifth Replacement Tariff*, Appendix D: Black Start Generating Units as of November 1, 2017, December 2017.
[17] Based on unit cold start times recorded on the 2016 version of Energy Information Administration Form 860.

providing black start need sufficient reactive power capability to support transformer inrush currents during the recovery process.

These characteristics related to the grid topology are summarized in Table 5.

Table 5. Summary of grid-related characteristics

Topological characteristic	Criterion	Consequence
Cranking path switching	A cranking path that can be established with *fewer switching actions* at substations is more favorable	Mitigates risk of unavailability of personnel required for switching Mitigates risk of inaccessibility of substations due to damage from event
Target generator reach	The capability for one black start plant to serve *multiple target generators* is more favorable	Provides more options for delicately balancing generation and load during the restoration process Mitigates risk of unavailability of specific target generators or cranking paths
Cranking path redundancy	The capability to reach a specific target generator *via multiple paths* is more favorable	Mitigates risk of unavailable cranking paths due to damage from event
Reactive power requirements	Short transmission lines to reduce line charging requirements and fewer large power transformers (LPTs) to reduce inrush current requirements are more favorable	Short lines and few LPTs reduce reactive power demands on the black start generator

Another characteristic related to grid topology is the proximity of the black start plant to the load center. Black start plants close to load centers tend to provide for more timely service restoration, owing to the less complex switching procedures to establish the connection and lower power requirements to meet the load demand.

3.3 Other Generating Technologies Not Usually Given Black Start Capability

This section discusses why some other technologies that can provide electric power are seldom given black start capabilities: nuclear power, solar (photovoltaic [PV]) and wind, and battery energy storage systems (BESSs).

Nuclear Power

Nuclear plants have large amounts of on-site generation (and secure fuel supplies) that are designed to provide station power if the plant must be taken offline and the grid cannot provide station power. However, these resources are designed to enable the plant to power down safely if there is a loss of off-site power (LOOP) event. The objective is to maintain the integrity of the reactor core; the essential equipment for doing so (e.g., cooling, control systems, monitoring) is normally provided by the grid when the plant is online or by the plant itself if the plant is separated from the grid (e.g., during a power system outage event). On-site diesel generators or turbines provide the power during shutdown mode if the grid is also down. The Nuclear Regulatory Commission (NRC) requires utilities to ensure that every nuclear plant has both on-site and off-site electric power sufficient to "… permit functioning of structures, systems, and components important to safety."[18] If the grid is insecure, on-site generators may be started in anticipation of a LOOP event.

Since the on-site generation resources are provided to enable the nuclear plant to shut down safely if the grid is unable to supply station power, for safety reasons, these resources cannot be used to black start the plant during a grid outage. Making a nuclear plant black start–capable, even by adding redundant on-site generators (and fuel supplies), would still violate NRC safety regulation requirements, because the plant is required to power down during a LOOP, not try to restart when the grid is insecure (i.e., not operating reliably).

Solar PV- and Wind-Powered Generation

Small-scale solar and wind systems, sited at end-user facilities or on distribution feeders/substations, can be valuable in providing power to facilities during a grid outage, but they are too small in power capacity (typically less than a few megawatts) to energize the transmission grid and serve as black start resources.

It is possible for large utility-scale wind farms and solar installations to provide black start power if equipped with advanced inverters and the necessary controls. While a system operator may indeed use such renewable energy generation to help reenergize the grid after a widespread outage, they cannot be regarded as *reliable* black start generators because of the unreliable nature of "as-available" generation from wind or solar, i.e., they cannot be assured of being available to generate power when black start services are needed. (i.e., not adequate wind speed or windspeed too high or not enough solar insolation such as during cloudy conditions). Even though many utility-scale renewable energy installations are equipped with a battery, the battery is designed to compensate for power output fluctuations due to the as-available nature of the power generated from wind and solar. Such batteries' nameplate capacities (both MW and MWh) are far too small to provide transmission system cranking power if the sun is not shining or the wind is not blowing or the wind speed is too for the wind turbine power production.

Battery Energy Storage Systems (BESS)

BESS have been installed at the distribution or substation level to compensate for local renewable energy resource output (the as-available nature of wind and solar) reduction, to reduce substation peak load and improve load factor, and/or to provide power to customers on the distribution level (e.g., through a microgrid) during a grid outage. As stated previously, BESS have also been installed at utility-scale renewable energy installations to smooth variations in renewable power production or alongside traditional thermal generators to increase flexibility. In

[18] Title 10, Code of Federal Regulations, Part 50, General Design Criterion 17, "Electric Power Systems," states "An on-site electric power system and an offsite electric power system shall be provided to permit functioning of structures, systems, and components important to safety… Electric power from the transmission network to the on-site electric distribution system shall be supplied by two physically independent circuits… One of these circuits shall be designed to be available within a few seconds following a loss-of-coolant accident to assure that core cooling, containment integrity, and other vital safety functions are maintained."

both scenarios, the BESS alone are too small to provide significant black start resources but could be utilized later in the restoration process to smooth frequency or voltage deviations. Additionally, during normal operations BESS are typically dispatched for economic benefits; thus there is no assurance that the BESS will still be charged in the event of an unexpected outage.

3.4 Operational Support

Established procedures are crucial to orchestrating the complex process of restoring power after a significant blackout event, as are the training and drilling tests of operators and plant staffs. These include the following:

- A "black start resource agreement" between the transmission operator and each generator operator with a black start resource, documenting the protocol for provision of black start services, including requirements for testing and training.
  - Documented procedure for starting each black start resource, energizing a bus, and configuring switchgear
  - Agreements and/or other procedures/protocols for off-site power requirements of nuclear power plants (these are usually specified in a nuclear plant's technical specifications)
  - Identification of cranking paths and initial switching requirements
  - Identification of acceptable voltage and frequency limits during restoration
  - Operating processes to restore loads that are required to restore the overall system, such as station service loads for substations, station service loads for units to be restarted; and loads needed to stabilize the generator's output, frequency, and voltage

- Telecommunication systems capable of effectively communicating with the transmission operator under black start conditions

> ***Objectives change during outage recovery***
>
> ***Normal operations:*** Minimize the cost of electricity while operating the grid in a safe, reliable, sustainable, and efficient manner.
> ***Outage recovery*** Minimize blackout duration while operating in a safe manner, not considering the economic consequences of out-of-merit power plant dispatch, or other actions.
>
> While low-cost electricity is desirable, including the provision of low-cost black start services, cost is not considered in the decisions an operator makes when recovering from a power outage.

3.5 Hydropower's Role in Historical Black Start Events

As part of its investigation into remedial actions adopted by the utility industry in the wake of a 1965 blackout in northern New York state and the province of Ontario, the Federal Power Commission surveyed utilities on the generally improvised methods by which they restarted their generating units (Figure 18). Of the companies responding, 45% reported use of hydropower plants—by far the most prevalent method of provisioning black start resources—as their source of emergency start-up power resources. The next most prevalent response (26%) was use of gas or diesel generators, followed by use of gas turbines (20%). At that time, 30% still reported dependence on an energized transmission system as their black start resource.[19]

[19] The total percentage is greater than 100% because some companies use more than one type of black start resource.

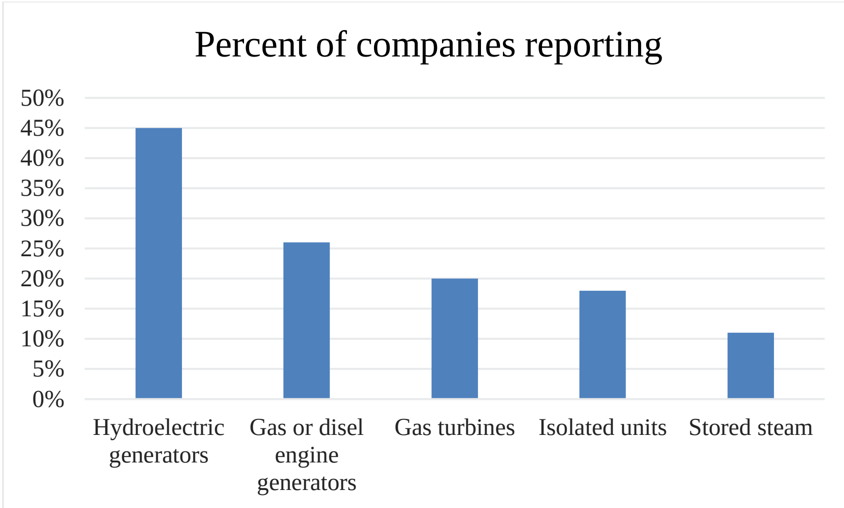


Figure 18. Methods of provisioning black start services following the 1965 blackout. *Source: Prevention of Power Failures—An Analysis of Recommendations Pertaining to the Northeast Failure and the Reliability of the U.S. Power Systems,* A Report to the President by the U.S. Federal Power Commission, July 1967.

According to the 1965 blackout report

> Where hydroelectric power is readily available, systems are relying upon, [*sic*] this source for quick start-up power, and some are arranging circuits for simplified switching in time of need. Systems with access to hydroelectric power were among the first to restore service on November 9.

More recently, a blackout on August 14, 2003,[20,21] triggered black start responses around the North American power system. In Michigan, Consumers Energy and Detroit Edison both invoked their local black start procedures—with Detroit Edison in the midst of a system-wide power outage. While the record shows that power systems were generally restarted by obtaining start-up power from neighboring power systems, the Ludington Pumped Storage facility was useful for moderating high system frequencies early in the restoration process.[22] Many generating units and electric loads are tuned to operate at a normal system frequency (in North America the standard is 60 cycles per second). Typically, large frequency-sensitive devices (generators and loads) are equipped with protective relays to interrupt their connection to the electric grid if the frequency varies outside the bounds of their operating range. These automatic protection-system actions usually are not part of the restoration plan. Although they protect the local equipment (which is their primary function), these actions can be detrimental to the restoration of the larger electric grid because the initial restoration may be characterized by large swings in frequency that cause the protective relays to trip. So, maintaining system frequency (and voltage and other parameters such as power factor and power quality) within tight bounds prevents "abandonment"

[20] Official investigative reports can be found at http://www.nerc.com/pa/rrm/ea/Pages/Blackout-August-2003.aspx (accessed April 3, 2018).
[21] US–Canada Power System Outage Task Force report can be found at https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/BlackoutFinal-Web.pdf.
[22] *Michigan Public Service Commission, Report on August 14th Blackout*, November 2003.

of the grid by large generators or loads and is critical to the successful restoration of the larger electric power system.

Blackout of August 14, 2003

The largest blackout to date affected 50 million people in the northeastern United States and southeastern Canada and interrupted more than 70,000 MW of load. Power was restored to most customers within hours, but parts of Ontario experienced rotating blackouts for up to 2 weeks.

This blackout had multiple causes: failure of a transmission owner to operate its system within appropriate limits and to adequately manage tree growth in a transmission right-of-way, inadequate situational awareness on the part of the transmission owner, and a failure of the reliability organizations to provide effective, real-time diagnostic support.

Since 1965, six major blackout events in North America have affected approximately 100 million customers (Figure 19 and Appendix A). Black start resources have played a critical role in restoring power and will continue to do so in the future.

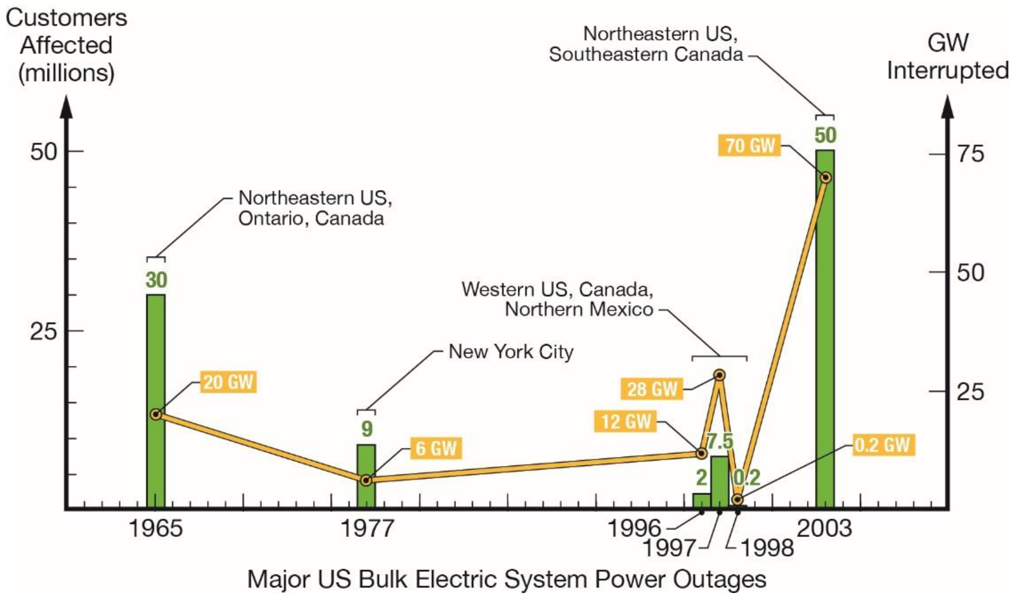


Figure 19. Major power outages of the US bulk electric system since 1965.

3.6 Current Role of Hydropower in Black Start Preparedness

As was learned from the 1965 blackout and more recent events, transmission grid operators must be prepared to restore power to the grid from a completely de-energized state. As in 1965, hydropower plants continue to be significant sources of black start power. Based on information available from the NERC Generating Availability Data System, 35 to 40%[23] of the units maintained and tested for black start are hydropower turbine-generators. As shown in Figure 20, although the majority of units tested for black start in the United States are gas turbines,

[23] Based on data from NERC Generating Availability Data System.

hydropower provides about 40% of the black start resources despite representing only about 10% of overall US generating capacity.

Hydropower continues to play a role in grid resilience because of its inherent ability to start quickly with minimal station service needed and constantly available "fuel" from waterways and reservoirs.

An additional advantage, due to the very small fleet of auxiliary equipment needed to run hydropower plants, is that they have a relatively sparse switching sequence that must be executed as part of the black start process.

The following are advantages of hydropower as black start resources:

- **Ability to start without an outside electrical supply**. Hydropower plants are among the easiest plants to start without an external power source, because little power is required to start the auxiliary systems. The auxiliary systems in hydropower plants are oil pumps for the bearing lubrication system and for the governor to move the wicket gate, air compressors, and field excitation coils. Hydropower plants do not have pulverizers (as in coal plants), draft fans, conveyors, or other energy-intensive processes that need to run before the generator is brought online. Gas turbines also do not need fuel handling equipment, but after they exhaust any gas supplies stored on-site, their continued operation requires that natural gas lines feeding the turbines be maintained at proper pressurization; this takes power. Therefore, the minimal auxiliary equipment at a hydropower plant reduces the magnitude of their station power, a significant advantage for hydropower over other types of generators.

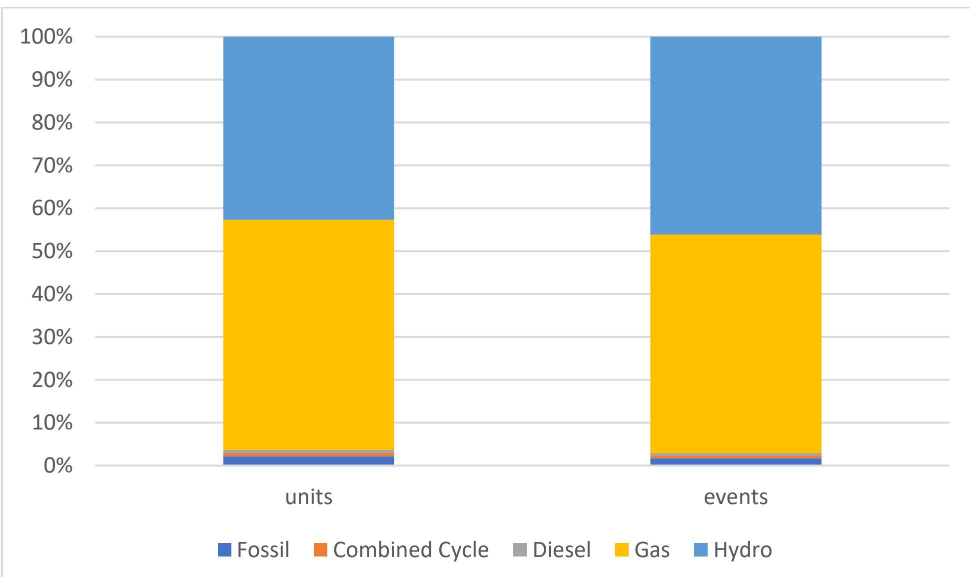


Figure 20. Makeup of black start units and events in the United States.

- **Short starting time**. For the reasons mentioned above, hydropower plants are characterized by rapid start-up times (as fast as 10 minutes), which makes them more favorable than other types of power plants, except gas turbines.

- **Sufficient real power capability**. Hydropower generating units are commonly of sufficient size to accommodate their own station service loads, as well as blocks of external loads to be added, without tripping offline because of a frequency dip. This is a function of the capacity of the unit, not the type of fuel.

- **Sufficient reactive power capability**. Hydropower generating units commonly have sufficient reactive power capability to accommodate the line charging current (significant reactive current caused by unloaded or lightly loaded transmission lines) and to feed the inrush currents of large power transformers (significant reactive current to establish the magnetic fields inside transformers). This is a function of the size of the unit and its reactive power profile (the "D-curve," which defines the real power versus reactive power capability of the generator), not of the type of fuel.[24]

- **Number of units at the black start power plant** (more is better). Hydropower plants commonly have many units (sometimes in the high teens or twenties), so it is extremely unlikely that there will not be enough units available for black start because of a forced outage or routine maintenance (at least to the extent that station service buswork accommodates multiple black start units). This is a significant advantage of hydropower facilities.

- **On-site fuel inventory of black start fuel** (more is better). Apart from the case of a severe drought, hydropower generating facilities have ready access to fuel (water flow, the primary energy source) for the black start generators. This enables hydropower plants to provide several rounds of black start service in cases when repeated attempts to restore the grid are required. Also, from a grid resilience standpoint, water flow is less likely to be interrupted than the availability of coal (for example, coal supply to a coal-fired plant was interrupted by a polar vortex freezing the coal piles[25]) or the natural gas supply (which can suffer from low pipeline pressure). This is another significant advantage of hydropower facilities. For the accessory diesel generators in hydropower plants, diesel fuel storage does not pose a problem, given the small size of the diesel generators required.

- **Switching required to initiate black start** (simpler/fewer operations are better). Because of the very small fleet of auxiliary equipment needed to run a plant, hydropower plants have a relatively sparse switching sequence that must be executed as part of the black start process.

- **Frequency support**. Hydropower units tend both to be more tolerant of system frequency excursions and to have significant inertia because of their large size (and variability of output) to help mitigate frequency swings and support voltage.

Note that, as part of satisfying dam safety requirements, any hydropower plant that is either federally owned or under FERC jurisdiction (most or all of the hydropower plants in the United States) must have an emergency generator on-site capable of operating the spillway gates (Figure 21). Such generators are also likely to be large enough to serve as black start generators (if the appropriate buswork/breakers were put in place). So, in addition to the hydropower units identified as black start resources in the transmission operating plan restoration plan, there may

[24] "Reactive Reserves and Generator D-Curves," PJM presentation, January 27, 2015.
[25] "Polar Vortex Review," North American Electric Reliability Corporation, September 2014.

be many more hydroelectric plants that would be capable of providing black start service with minimal changes to the plant and operating procedures.

Figure 21. Workers installing a 500 kW emergency generator at Davis Dam. *Source:* US Bureau of Reclamation, photograph # B351-300-20437

For hydropower plants acting as black start resources, location would be a constraint and concern for some transmission operators, especially in densely populated areas. By its nature, a hydropower plant relies on the appropriate water resources, most of which lie in suburban or rural areas. In 2017, a study by the Pacific Gas and Electric Company in California identified eight drivers of electric grid restoration risk, and one of them is that "*current black-start resources are hydro generation—remote from critical load centers and Diablo Canyon Power Plant.*" [26] In the first level of the NYISO restoration plan, hydroelectric units in the central, northern, and the western part of the state are the major black start resources. However, an area like New York City, for example, needs more local black start resources for the accelerated restoration of electric service.[27]

[26] ER17-2154, *Order Accepting and Suspending Proposed Tariff Revisions and Establishing Hearing and Settlement Judge Procedures*, Exhibit pg-0003 attached with the transmittal letter.
[27] ER15-563, *Order Accepting Tariff Revisions and Granting Waiver*, January 30, 2015.

4.0 Regulatory Drivers of Black Start Services

NERC is the body responsible for promulgating the technical standards that govern the operation of the bulk electric power system. According to NERC [28]:

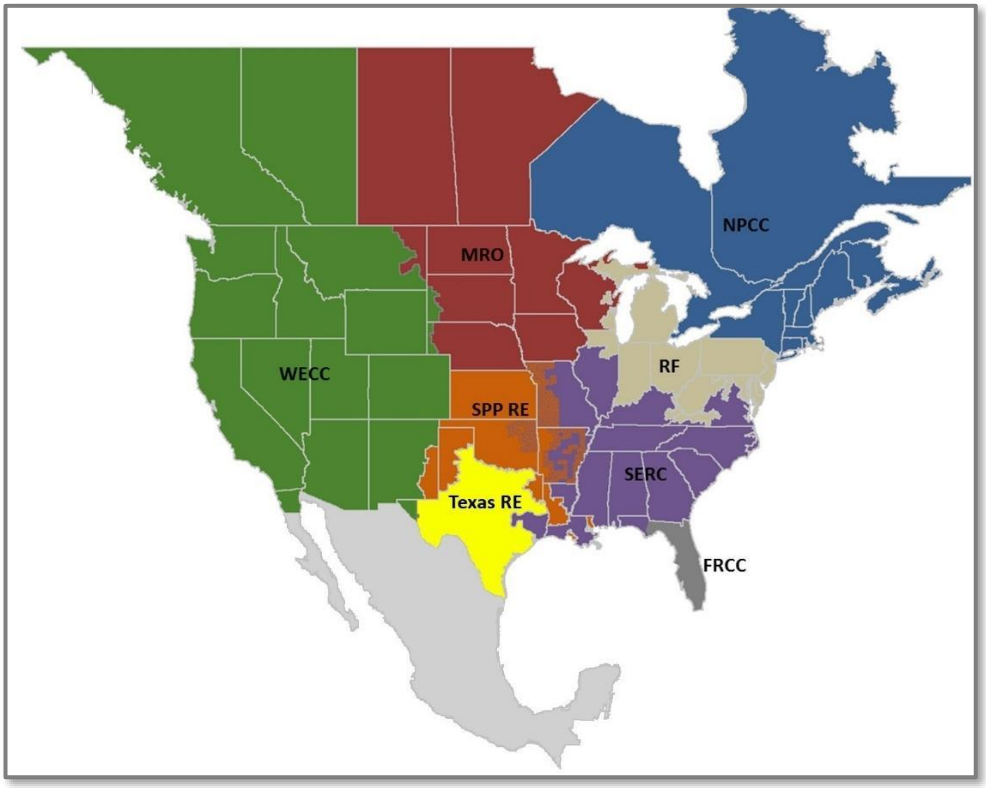
> The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the Electric Reliability Organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.
>
> The North American BPS is divided into eight Regional Entity (RE) boundaries, as shown in Figure 22.
>
> Black start plans are driven by NERC standards. NERC's definition of a black start resource is "a generating unit(s) and its associated set of equipment which has the ability to be started without support from the System or is designed to remain energized without connection to the remainder of the System, with the ability to energize a bus, meeting the Transmission Operator's restoration plan needs for Real and Reactive Power capability, frequency and voltage control, and that has been included in the Transmission Operator's restoration plan."[29]

The following are the NERC standards that explicitly relate to black start, along with descriptions.

- NERC Standard EOP-005-3: System Restoration from Black Start Resources
  - **Purpose:** Ensure plans, facilities, and personnel are prepared to enable system restoration from black start resources to ensure reliability is maintained during restoration and priority is placed on restoring the interconnection.
  - **Applicability:** Transmission operators, generator operators, transmission owners identified in the transmission operators restoration plan, and distribution providers identified in the transmission operators restoration plan.

[28] *State of Reliability 2017*, North American Electric Reliability Corporation, June 2017.
[29] *Glossary of Terms Used in NERC Reliability Standards*, NERC, updated October 6, 2017.

- NERC Standard EOP-006-3: System Restoration Coordination
  - **Purpose:** Ensure plans are established and personnel are prepared to enable effective coordination of the system restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the interconnection.
  - **Applicability:** Reliability coordinators.



FRCC = Florida Reliability Coordinating Council, MRO = Midwest Reliability Organization, NPCC = Northeast Power Coordinating Council, RF = Reliability First, SERC = SERC Reliability Corporation, SPP RE = Southwest Power Pool Regional Entity, Texas RE = Texas Reliability Entity, WECC = Western Electricity Coordinating Council

Figure 22. The eight regional entities of the North American bulk power system.[30]

- NERC Standard EOP-007-0: Establish, Maintain, and Document a Regional Black start Capability Plan
  - **Purpose:** A system black start capability plan is necessary to ensure that the quantity and location of system black start generators are sufficient and that they can perform their expected functions as specified in overall coordinated regional system restoration plans.
  - **Applicability:** Regional reliability organization.

[30] The regional boundaries in this map are approximate. The highlighted area between SPP and SERC denotes overlap, as some load-serving entities participate in one region while associated transmission owners/operators participate in another

- NERC Standard EOP-009: Documentation of Black Start Generating Unit Test Results
  - **Purpose:** A system black start capability plan is necessary to ensure that the quantity and location of system black start generators are sufficient and that they can perform their expected functions as specified in overall coordinated regional system restoration plans.
  - **Applicability:** Generator operator, generator owner.

The units and plants designated as black start resources are considered fundamental elements of the electric infrastructure to provide the continued operation of the national power system (and, consequently, of the modern economy). As such, they must adhere to stringent standards, devised to ensure both their physical and cyber security, in accordance with the Critical Infrastructure Protection (CIP) program.

- The primary CIP standard applicable to black start plants is **NERC Standard CIP-014:** Physical Security
  - **Purpose:** To identify and protect transmission stations and transmission substations and their associated primary control centers that, if rendered inoperable or damaged as a result of a physical attack, could result in instability, uncontrolled separation, or cascading outages within an interconnection.
  - **Applicability:** Transmission owner (select), transmission operator (select).

Several additional CIP standards are applicable to black start resources, including CIP-003-6 and 7, CIP-004-6, CIP-005-5 and 6, CIP-006-6, CIP-007-6, CIP-008-5, CIP-009-6 CIP-010-2 and 3, CIP-011-2, CIP-013-1, PRC-019-2, and PRC-025-2.

These NERC standards represent the primary requirements that must be met and from which other requirements may be devised. Many grid service regions are unique in their physical topology, makeup of electricity customers, presence of critical loads, power plant fleet, transmission system configuration, and regulatory framework. Therefore, NERC regional entities and transmission operators may customize standards and procedures to meet the NERC requirements in a way that best meets the local constraints.

Testimony[31] by FERC to the Senate Committee on Energy and Natural Resources shows that evaluation of black start resources is ongoing:

> Beginning in September 2014, Commission staff has been collaborating with NERC, Regional Entities, utilities and grid operators on a series of studies and reports regarding restoring the grid after a widespread blackout. The motivation for the initial study was to get a comprehensive understanding of the electric utility industry's bulk power system recovery and restoration planning, focusing specifically on the reliability standards relevant to system recovery and restoration, which require entities to develop and test plans for recovery and restoration. To do this, Commission staff worked collaboratively with staff from NERC and the Regional Entities to review the plans for recovery and restoration of utilities of participating utilities…Since the release of the initial study in

[31] "Testimony of David S. Ortiz, acting director of Electric Reliability, Federal Energy Regulatory Commission, before the Committee on Energy and Natural Resources. United States Senate, October 11, 2018.

January 2016, the joint study team has released two additional studies. The latest study, focused on black start…

In May 2018, staff released the *FERC-NERC-Regional Entity Joint Review of Blackstart Resources Availability (BRAv).* This study took a close look at: '(1) the availability of black start resources, including the identification of strategies for replacing these resources going forward and the factors to be considered for such replacement resources; and (2) options for expanding system restoration plan testing beyond the currently required black start resource testing, to ensure that a black start resource can energize equipment necessary to restore the system as intended in the restoration plan.' The study also included an assessment of registered entities' black start resource testing under anticipated black start conditions to ensure that these resources can effectively restore the bulk power system following a widespread outage.

The study concluded that although some participants have experienced a decrease in the availability of black start resources due to retirement of black start-capable units over the past decade, the participants have verified they currently have sufficient black start resources in their system restoration plans, as well as comprehensive strategies for mitigating against loss of any

additional black start resources going forward. The study also found that participants that have performed expanded testing of black start capability, including testing energization of the next-start generating unit, gained valuable knowledge that was used to modify, update and improve their system restoration plans. Participants also used the knowledge gained to update and improve their existing steady state and dynamic models of those plans, as well as their system restoration drills.

The study recommended that utilities perform expanded testing of black start cranking paths where feasible."

5.0 Compensating Black Start Resources

5.1 Black Start Service Costs

There are, of course, costs involved in providing black start capabilities: these may be placed into two categories:

- Initial capital costs
- Ongoing operations and maintenance costs

Initial costs are one-time costs associated with equipping a power plant with the features required to provide black start services. These include the costs of installing emergency start-up generators (e.g., diesel generators in hydropower plants), additional buswork and circuit breakers internal to the plant to provide the switchgear and circuits necessary to power the black start unit(s), additional communication gear driven by the need to coordinate activities with system operators when restoring a power system in outage, security upgrades to accommodate requirements of NERC CIP-014,[32] and other similar one-time costs.

Ongoing costs are the recurring costs associated with maintaining the power plant, associated systems, and staff readiness specifically related to black start services. These include costs to provide the labor required to perform black start drill tests, maintain power and telecommunications equipment, manage the black start fuel supply/storage, maintain up-to-date operational and technical procedures, maintain current contractual/financial agreements with other stakeholders, and provide fuel to run the plant as a black start resource (during tests or actual operation).

Black start costs may also include the cost of upgrading the transmission path(s) between the black start plant and the target plant(s), and the cost of complying with the security requirements of NERC CIP-014.

5.2 Compensation Mechanisms

Under the typical vertically integrated utility model of electricity supply and delivery, costs to provide black start capabilities were passed on to customers through electricity rates negotiated with a public utility commission. Initial costs were capitalized and compensated at a negotiated rate of return, and ongoing expenditures such as those for training and testing would be recouped as they were incurred. However, after the electricity market deregulation in the late 1990s and early 2000s, significant portions of the country lacked compensation mechanisms to ensure the continued maintenance of black start resources. Efforts to ensure black start reliability in these restructured markets began as early as 1996, with proposals[33] to FERC to create a "restoration" service. Over time, all major ISO/RTO regions established black start as a dedicated ancillary service compensated under their open access transmission tariffs.

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[32] NERC Standard CIP-014, *Physical Security*.

[33] The New England Power Pool submitted the first proposal in 2000 (FERC ER00-2485, FERC ER00-1572). PJM (Pennsylvania, Jersey, Maryland) followed in 2002 (FERC ER02-2651). Other markets followed suit.

In 2011, FERC approved a NERC petition[34] to establish three new reliability standards (EOP 001-1, EOP 005-2, and EOP 006-2) and "black start resource" as a new definition term. These new requirements, effective on July 1, 2013, became the main policy driver of many recent plan developments, tariff revisions, and requests for proposals related to black start resources.[35]

The mechanics of compensating generator owners and generator operators for black start costs varies between ISO/RTOs, but they can be classified under three primary approaches:

1. **Cost recovery**: Similar to historical approaches in vertically integrated markets, under cost recovery provisions, owners are compensated for the actual capital and operations and maintenance (O&M) costs incurred to install and maintain black start capability.

2. **Standard payment**: Simplifying the compensation scheme, the standard payment compensation provides a flat rate payment to black start units. These payments typically involve a capital recovery component (for eligible generators), an O&M component, and additional standard payments for NERC CIP compliance costs. These costs may vary among technology types. Hydropower is typically considered a lower-cost resource to provide black start and is consequently compensated at a lower rate.

3. **Economic payment**: Compensation levels for black start generators are determined based on prices submitted to an auction or request for proposals.

Table 6 qualitatively categorizes the black start compensation mechanisms used in each ISO/RTO.

Table 6. Summary of black start compensation in different markets.

Market	Tariff type	Unit size classification	Technology differentiation	Initial term of commitment
ISONE	Standard payment	7 +2 classes	Fossil, Hydroelectric	≥1 year or unit age based
PJM	Cost recovery	Not mentioned	Combustion turbine, hydro	≥ 2 years
NYISO (Con Ed)	Standard payment	7 classes	Not mentioned	3 years
CAISO	Cost recovery	Not mentioned	Not mentioned	Not mentioned
ERCOT	Economic payment	Not mentioned	Not mentioned	2 years
MISO	Cost recovery	Not mentioned	Not mentioned	≥3 years

ISONE = ISO New England; PJM = Pennsylvania, Jersey, and Maryland; NYISO = New York ISO; CAISO = California ISO; ERCOT = Electric Reliability Council of Texas; MISO = Midcontinent ISO.

[34] 134 FERC 61215 (Order 749).

[35] ER11-4514, MISO (Midcontinent ISO) revised black start resources tariff; ER12-2302, MISO further clarified the black start resource requirements; ER12-2568, NYISO revised its Black Start and System Restoration Service Tariff; ER13-699, CAISO (California Independent System Operator) proposed Tariff Amendment—Blackstart and System Restoration Plan; ER13-1535, San Diego Gas & Electric Company changed black start service agreement with CAISO; ER13-1796, Pacific Gas and Electric Company proposed to change the black start agreement with CAISO; ER13-1821, Southern California Edison Company changed black start agreement with CAISO; ER15-563, NYISO amended tariff and required black start resources within New York City; ER17-2237, CAISO reorganized its black start and system restoration tariff and procure black start resource in the Bay area; ER17-2271, NYISO enhanced the testing procedure of black start service and related tariff.

Some key similarities and differences emerge among markets, including these:

- **Differentiation of black start compensation based on unit capacity:** All else being equal, larger units require larger upfront capital costs and higher ongoing O&M costs to ensure black start capability. In markets that use the "standard payment" approach to compensating black start units, multiple tiers of payments are required to capture this increasing cost basis. Markets that compensate black start resources according to the standard payment approach, such as ISONE and portions of NYISO, bin the standard payments into capacity groupings (e.g., 10 to 60 MVA, 60 to 90 MVA, and greater than 90 MVA).

- **Compensation caps:** Some individual cost elements in black start plants do not scale as strongly with capacity, such as NERC CIP requirements, and therefore have caps placed on their maximum level of compensation.

- **Differentiation of black start compensation based on unit technology type:** The capital and O&M costs for black start resources also vary based on the technology configuration of a unit. Fossil fuel black start units must retain dedicated fuel reserves and storage infrastructure to meet NERC standards, and units with higher station service loads require larger generators to meet their starting requirements. Therefore, markets that use standard payments further bin resources based on the magnitude of starting power needs. As hydropower units typically have the lowest station service loads of any technology and do not require additional storage infrastructure, they are generally the least expensive option for black start.

In addition to the mechanisms by which compensation is determined, a major consideration in the sustainability and adequacy of black start payments is in the duration of the contractual term. Some generators and analysts have suggested that the limited duration of black start contracts used in some markets (such as the Electric Reliability Council of Texas biennial procurement process) adds a substantial element of risk to generation operators seeking to invest in new black start capabilities.

After years (and in some cases decades) of revisions, black start tariff designs continue to evolve. In the spring of 2018, a joint study team initiated by FERC, NERC, and regional entities assessed the state of black start resource procurement and replacement.[36] According to their findings, most of the black start service providers in organized markets were providing some compensation for black start; but participants cited additional concerns, including limited incentives for fully depreciated units to provide black start service, challenging and expensive filing processes to obtain the approved rate, and absence of compensation for the additional black start units in a single plant. One recommendation suggests that new compensation mechanisms be introduced for "next-start" units (target units of black start units) to cover their participation in testing of restoration plans. Finally, it is important to consider that the compensation itself needs be computed based on actual cost data (which may vary significantly). Some further details of this topic are provided in Section 5.3.

[36] *Report on the FERC-NERC-Regional Entity Joint Review of Restoration and Recovery Plans Recommended Study: Blackstart Resource Availability*, May 2018, https://www.ferc.gov/legal/staff-reports/2018/bsr-report.pdf

5.3 General Context for Black Start Cost and Compensation

While black start is an essential reliability service, compensation for it is not a substantial component of revenue at the plant level and an even lesser cost center at the system level. To illustrate the former issue, Figure 23 shows the revenue composition for a dispatchable hydropower project—Lake Lynn, an approximately 50 MW project in Pennsylvania, Jersey, Maryland (PJM)—where black start payments account for only $1.17/kW of revenue per year, less than 1% of the project's total revenue.

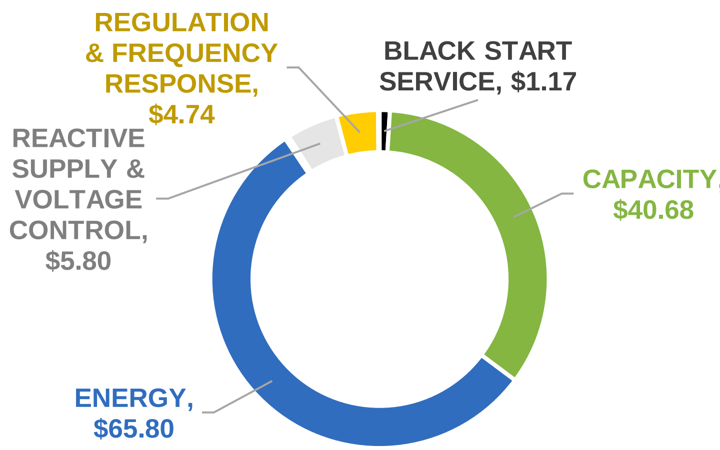

Figure 23. 2016 Revenue composition ($/kW) for the Lake Lynn hydropower project.

The limited contribution from black start compensation to the overall Lake Lynn project budget is no exception. Other projects within PJM are also compensated at low levels on a relative $/kW basis. For example, the Big Sandy Peaker project (a plant with six 59 MW gas turbines) recorded black start compensation of $1.56/kW; and two pumped storage projects — Yards Creek (three 151 MW units) and Seneca (two 220 MW units) have compensation rates of $0.38 and $1.17 per kW, respectively.[37] Differences in these rates are attributable to the number of units at a plant eligible for black start, differences in technology and installed capacity, and any capital investments necessary to meet NERC black start and CIP standards.

At the system level, black start is a minimal contributor to the overall cost of service, as seen in Figure 24, which displays the total compensation paid to black start generators in PJM from 2008 to 2017.

[37] Lake Lynn and other PJM plant reference value estimates are derived from actual node or holding-company-level transactions extracted from FERC electronic quarterly reports for 2016. Accessed March 2018.

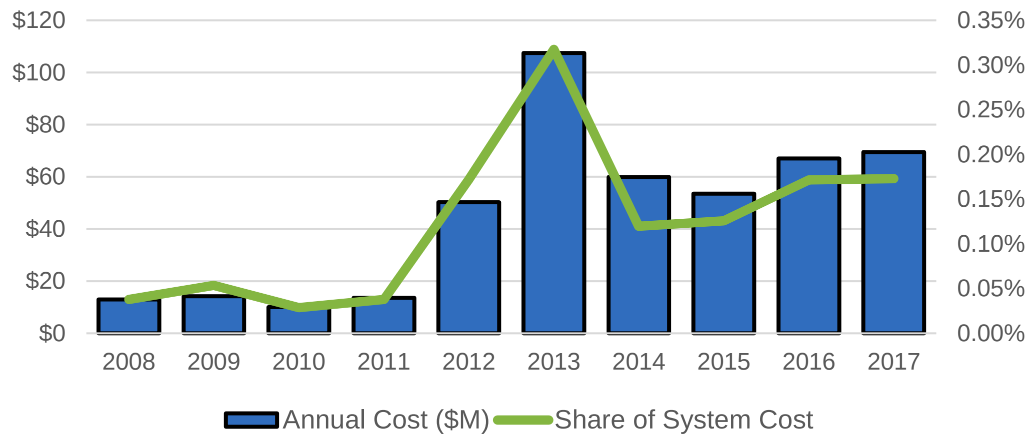

Figure 24. The total cost of black start in PJM.

Black start–specific costs have ranged from $10M/year to $110M/year in PJM. The distinct jump seen between 2011 and 2012 is a product of accounting changes whereby certain operational costs previously categorized under other services became more granularly assigned to black start. These costs include revenues lost from time spent conducting annual black start capability tests and unprofitable operations that were necessary for a specific type of black start resource unique to utilities within the PJM footprint.[38] The 2012–2013 spike corresponds to payments necessary to coal units being operated outside of "merit order" (i.e., competitive economic dispatch) to provide black start. These plants became economically unsustainable owing to lower natural gas prices.

While market-to-market variations exist in procurement and compensation practices, two decades of experience with procuring black start resources appears to have led to a relative convergence of costs between markets with different payment mechanisms. To illustrate this point, Figure 25 shows the system-wide payments for black start in PJM (cost-recovery based) and ISONE (standard-payment-based). These costs were normalized on an annual basis by dividing the total cost of black start for each ISO/RTO by its peak demand for the year. Since 2012, the cost per peak megawattage of providing black start has ranged from $300/MW to $700/MW in both PJM and ISONE. In recent years, this value has converged to approximately $500/MW of peak demand in both markets.

[38] In PJM, certain coal units—those equipped with "alternative load rejection" (ALR) capabilities—are contributors to black start reliability. In the technology requirements documented in Section 3, central thermal plants, such as coal boilers, would typically be less desirable for black start owing to longer startup times and higher station service loads. In contrast, ALR units avoid these limitations by technically never needing to "start." Instead, these units must run 24/7, but they are able to continue operation at low power levels following a blackout and increase power as necessary to restore the remainder of the grid.

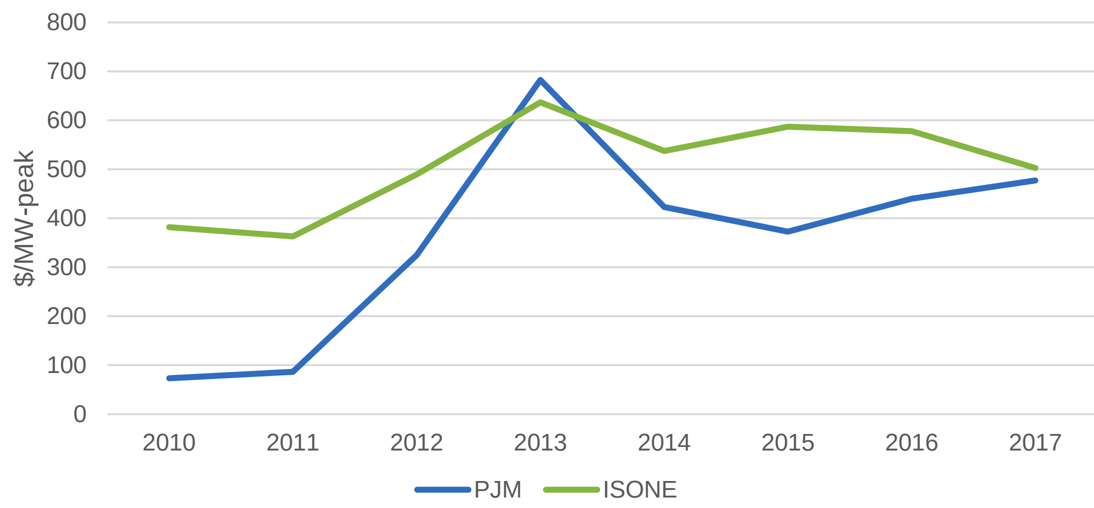

Figure 25. System restoration cost/black start cost in ISONE and PJM from 2010 to 2017.

These considerations show that because the current black start compensation cost is factored as a very small fraction of the energy production cost, even a significant percentage increase in compensation would have minimal cost impact on consumers (and/or could be easily absorbed by the operator). On the other hand, black start compensation could provide a significant benefit, as the availability of black start resources could proportionally be increased by the same (or a related) percentage amount.

6.0 Conclusions

The power blackout of 1965 in the northeastern United States served as a wake-up call regarding the need to be able to black start a power system. Subsequent major blackouts have reinforced the need to have appropriate and reliable black start resources and grid restoration plans/procedures in place. Restoring the grid requires first having a black start plan in place. This includes having adequate generators capable of being self-started without grid-supplied station power; pre-tested plans for jump-starting the grid by using black start units to supply station power to more generators through pre-defined cranking paths; extensive training and procedures to enable power system personnel at all levels to respond to severe and ill-defined emergency situations; and situational awareness for system operators (monitoring, communications and control systems) to implement and modify restoration plans in response to changes in status.

Industry and regulatory efforts (e.g., NERC, FERC) have set standards and requirements for grid reliability, restoration and resilience, including provision for and deployment of black start resources. Those standards and procedures continue to evolve, along with advances in monitoring and controls (e.g., deployment of synchrophasor technology), changes in grid topology, increased deployment of newer and distributed power generation and storage technologies, increased reliance of society and its infrastructure on electricity from the power system, and appreciation of threats (natural and man-made) to and vulnerabilities of the electric power grid.

This report introduces the concept of black start and the advantages of hydropower plants as black start resources. Also the report describes the procedures and considerations for black starting the grid after a major blackout, summarizes technical characteristics of generators suitable for black start, cites key regulatory organizations and requirements related to black start, and provides some examples of the economics of both providing black start resources compensating black start providers.

The favorable characteristics of candidate black start generators include

- Small station power requirements (e.g., systems for fuel handling, cooling, emission control, monitoring and control, communications)
- Fast restart
- Large real and reactive power capacity
- Adequate on-site fuel supply
- Ability to operate during frequency excursions
- Ability to stabilize system frequency (size, inertia, ramp rate) and support voltage
- Direct transmission connections with other generators

Thus, the ideal black start unit has the following capabilities:

- Needs minimal time, fuel, and equipment to restart
- Can be relied upon to be available for black start, with fuel on hand
- Is large enough in generation size (nameplate capacity) to provide real and reactive power to energize the transmission system and restart other generators
- Can provide station and start-up power to other generators with a minimum of transmission switching and transformation operations required
- Can operate during early grid restoration operations, when frequency swings are expected, and can help stabilize system frequency and support voltage

The following list indicates how well various generation technologies match those desirable characteristics:

- **Hydroelectric** power plants meet all the desired attributes for black start: Their “fuel”—water—is always available (unless a severe drought impacts lake levels and reduces the head for the plant), their station power requirements are low, restart is fast and simple, and they can operate efficiently in the early stages of restoration, when system frequency is not stable.
- **PSH** units have almost all the advantages of conventional hydro units. However, economical dispatch may have depleted the upper pond of a PSH facility, so PSH units are not certain to have adequate resource energy available for black start unless some water is always held in reserve.
- **CT** technology provides the majority of black start capability in the nation. CTs can be restarted quickly and vary their power output quickly. However, they are dependent on having available fuel supply (a pressurized natural gas pipeline in service).
- **Combined cycle** units can be used for black start, but they require several hours to restart, have more complex cooling requirements (i.e., higher station service load), and are dependent on having available fuel supply (a pressurized natural gas pipeline in service).
- **Coal-fired plants** are typically not equipped for black start. They take hours to restart and have very large station service requirements (especially for fuel processing/handling and cooling).
- **Nuclear power plants** are not good candidates for black start for safety and regulatory reasons.
- **Utility-scale renewable energy sources (solar PV– and wind-powered generators)** cannot be relied upon as black start resources because their energy sources may not be available when needed. Although they may be able to provide black start after an outage if they are suitably equipped, e.g., with energy storage, they cannot be considered an assured resource for planning purposes.

- **Distribution-level BESS** resources can be invaluable in restoring service to selected customers or feeders/microgrids after an outage. As the grid recovers, and electrical islands are reconnected, having already energized and operating substations via BESS will speed overall grid restoration. However, these installations are too small in capacity to be considered as black start resources.

Hydroelectric power plants' characteristics are particularly well suited to ensuring that the power grid has adequate and appropriate resources to support black start operations. Historically, power systems have relied heavily on hydro plants to provide black start capability, and the preponderance of hydro units supplying black start continues to this day. About 40% of the units in the United States maintained and tested for black start are hydropower turbines. This is significant because hydropower comprises only about 10% of overall US generating capacity.

Although black start services are critical to the recovery from a major blackout, in general the need for additional black start services is limited because rigorous industry and regulatory standards have ensured coverage. Once a region has identified sufficient black start resources to restore its system (including redundancies to account for unavailable black start generating resources and cranking paths), adding more black start units does not significantly improve the risk profile of that region. Opportunities for new black start resources arise when the served load grows (e.g., owing to a population increase and/or to new industrial and commercial end-users), when existing black start units are decommissioned, or when re-evaluations of grid reliability and resilience in response to new natural or human-made threats indicate.

It should be also recognized that if a black start plant has been designated as a critical asset according to the NERC CIP standards, the regulatory scrutiny and compliance burdens for that power increase.

Appendix A

Examples of Major Bulk Electric System Power Outages

Appendix A. Examples of major bulk electric system poer outages.[1]

Date	States/provinces affected	Customers affected	Duration	Description
November 9, 1965	Virtually all of New York, Connecticut, Massachusetts, Rhode Island, and small segments of northern Pennsylvania and northeastern New Jersey; substantial areas of Ontario, Canada	30,000,000; over 20,000 MW of demand	Up to 13 hours	A backup protective relay operated to open one of five 230 kV lines taking power north from the Beck plant in Ontario to the Toronto area. When the flows redistributed instantaneously to the remaining four lines, they tripped out successively in a total of 2.5 seconds. The resultant power swings resulted in a cascading outage that blacked out much of the US Northeast
July 13, 1977	New York City	9,000,000 people; 6,000 MW of demand	Up to 26 hours	A series of events triggering the separation and total collapse of the Con Ed system began when two 345 kV lines on a common tower line in northern Westchester were struck by lightning and tripped out. Over the next hour, the Con Ed dispatcher tried to save his system, but in the end the system electrically separated from surrounding systems and collapsed. Generation inside New York City was not adequate, by itself, to serve the load inside the city
July 2, 1996	Arizona, California, Colorado, Idaho, Montana, Nebraska, Nevada, New Mexico, Oregon, South Dakota, Texas, Utah, Washington and Wyoming in the United States; Alberta and British Columbia in Canada; and Baja California Norte in Mexico	2,000,000 (10% of the customers in the Western Interconnection); 11,850 MW of demand	From a few minutes to several hours	The outage began when a flashover occurred between a 345,000 V transmission line and a tree that had grown too close to the line in Idaho. Protective devices detected the short and de-energized the line. A protective relay on a parallel transmission line also detected the fault and erroneously opened the second line. Disconnecting these two lines nearly simultaneously greatly reduced the ability of the system to carry power away from a nearby generating plant, causing other protective devices to shut down two of the four generating units at that plant. With the loss of these two units, frequency in the entire Western Interconnection began to decline. For 20 seconds, the system struggled to remain in balance, but the system was becoming unstable. At this point, automatic protection systems were initiated to allow the system to bend, but not break. Scattered customer outages occurred to help the system regain balance. The interconnected system separated into five pre-engineered islands designed to minimize customer outages and restoration times

[1] Adapted from the North American Electric Reliability Corporation web site, accessed April 2, 2018. https://www.nerc.com/pa/rrm/ea/August%2014%202003%20Blackout%20Investigation%20DL/BlackoutTable.pdf

Appendix A. Examples of major bulk electric system power outages (continued).

Date	States/provinces affected	Customers affected	Duration	Description
August 10, 1996	Arizona, California, Colorado, Idaho, Montana, Nebraska, Nevada, New Mexico, Oregon, South Dakota, Texas, Utah, Washington and Wyoming in the United States; Alberta and British Columbia in Canada; and Baja California Norte in Mexico	7,500,000 customers; 28,000 MW of demand shed by underfrequency load-shedding relays	Up to 9 hours	Triggered by a combination of random transmission line outages and resulting system oscillations, the Western Interconnection separated into four electrical islands, with significant loss of load and generation. Before the disturbance, the 500 kV and underlying interconnected transmission system from Canada south through Washington and Oregon to California was heavily loaded because of (1) relatively high demand caused by hot weather throughout much of the Western Electricity Coordinating Council region and (2) excellent hydroelectric conditions in Canada and the Northwest that led to high electricity transfers (including large economy transfers) from Canada into the US Northwest and from the Northwest to California. Failure to trim trees and remove others identified as a danger to the system caused flashovers (short circuits) from several 500 kV transmission lines, the last of which led to overloads and cascading outages throughout the Western Interconnection. Also, operators were unknowingly operating the system in a condition in which one line outage would trigger subsequent cascading outages because adequate operating studies had not been conducted
June 25, 1998	Minnesota, Montana, North Dakota, South Dakota and Wisconsin in the United States; Ontario, Manitoba and Saskatchewan in Canada	152,000 customers; 950 MW of demand	19 hours	A severe lightning storm in Minnesota initiated a series of events, causing a system disturbance that affected the entire Mid-Continent Area Power Pool Region and the northwestern Ontario Hydro system of Northeast Power Coordinating Council. Lightning struck a 345,000 V line, and system protection de-energized the line. Underlying lower-voltage lines began to overload, and protective devices began to de-energize those lines, further weakening the system. Shortly thereafter, lightning struck a second 345,000 V line, taking that line out of service. Following the outage of the second 345,000 V line, the remaining lower-voltage transmission lines in the area became significantly overloaded and system protection began removing them from service. This cascading removal of lines from service continued until the entire northern Midcontinent Area Power Pool region was separated from the Eastern Interconnection, forming three islands and resulting in the eventual blackout of the northwestern Ontario Hydro system

Appendix A. Examples of major bulk electric system power outages (continued).

Date	States/provinces affected	Customers affected	Duration	Description
August 14, 2003	Ohio, Michigan, New York, Pennsylvania, New Jersey, Connecticut, Massachusetts, Vermont, and the Canadian provinces of Ontario and Québec	50 million people and more than 70,000 MW of electrical load	Power was successfully restored to most customers within hours. Some areas in the US did not have power for 2 days. Parts of Ontario experienced rotating blackouts for up to 2 weeks	There are four groups of causes for the blackout: Group 1: FirstEnergy (FE) and East Central Area Reliability Coordination Agreement failed to assess and understand the inadequacies of FE's system, particularly with respect to voltage instability and the vulnerability of the Cleveland–Akron area, and FE did not operate its system with appropriate voltage criteria. Group 2: Inadequate situational awareness at FE. FE did not recognize or understand the deteriorating condition of its system. Group 3: FE failed to manage adequately tree growth in its transmission rights-of-way. Group 4: Failure of the interconnected grid's reliability organizations to provide effective real-time diagnostic support

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