2017 Black Start Study

ISO New England

2017 Black Start Study
Project No. 101421

Revision 1
January 2018

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prepared for

ISO New England
2017 Black Start Study
Holyoke, Massachusetts

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January 2018

prepared by

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1.0 INTRODUCTION

ISO New England (ISO-NE) has requested that Burns & McDonnell (BMcD) assist in their Black Start Restoration Project to ensure the longevity of their current Restoration Plan and the sustainability of the black start fleet. Although ISO-NE is currently in compliance with black start/reliability requirements, they are proactively evaluating the necessity for additional black start capabilities and evaluating the economics to convert existing plants in the ISO-NE territory. ISO-NE currently has a rate structure in place but would like to confirm that it appropriately compensates existing black start resources and provides adequate incentives for other generators to add black start capabilities to their plants. This letter report documents the conceptual design and budgetary cost estimates for various generator sizes to evaluate in comparison to their current rate structure. The black start options evaluated in this assessment include the following:

- Hydro Plant
- <10 MVA - 1 x Wartsila 34DF Engine
- 10-60 MVA - 1 x Simple Cycle GE LM2500
- 60-90 MVA - 1 x Simple Cycle GE LM6000
- 90-300 MVA Small - 1 x Simple Cycle GE LMS100 or 2x1 Combined Cycle GE 7EA
- 90-300 MVA Medium - 2x1 Combined Cycle Siemens 501F
- 90-300 MVA Large - 1 x Simple Cycle GE 7FA.05 or 2x1 Combined Cycle GE 7FA.05
- 300+ MVA - 1 x Simple Cycle GE 7HA.02 or 2x1 Combined Cycle GE 7HA.02
- VSC-HVDC
- Storage Technologies

If an existing plant decides to implement a black start project, during a system restoration the plant may be subject to various risks until the grid is fully stabilized. BMcD commented on these risks and potential impacts to the plant.

It is the understanding of BMcD that this study will be used for preliminary evaluation of their existing rate structure. The options presented are intended to be representative of the generator size ranges. Depending on the specific plant to be converted, site specific implications may affect the overall project cost. Capital costs were developed by adjusting the diesel generator size and supporting facilities of known reference projects to represent the options presented in this study.

1.1 Background

ISO-NE is required to maintain a restoration plan to conduct initial restoration of the electrical system in the event of a system blackout. ISO-NE is currently in compliance with current North American Electric Reliability Corporation (NERC) and Northeast Power Coordinating Council (NPCC) reliability standards. In order to maintain compliance and meet the future requirements for system restoration, ISO-NE is planning to bring additional black start generators into the system restoration plan. This study provides up to date costs for the current diesel generator market as well as evaluation of other technologies that could be utilized to either black start an existing generation site or support the grid during a restoration event.

In order to incentivize generators to add black start capabilities to their facilities, ISO-NE developed a cost based rate structure to compensate generators for adding black start equipment. Part of developing the rate was understanding the costs incurred by existing black start generators in order to provide black start service. The existing generators must meet NERC regulations for training, recordkeeping, and testing in order to maintain their black start status. A questionnaire was issued to all black start generators in the ISO-NE area requesting information regarding black start specific costs. The information from the questionnaires was used to quantify certain incremental fixed O&M costs associated with a black start facility. Other fixed O&M costs categories were based on in-house BMcD information and information from diesel generator suppliers.

BMcD also developed capital costs for the options listed above. The capital costs were developed based on in house information and supplier information. The capital costs are based on a generic brownfield plant and quantify the costs for the major equipment classifications.

1.2 Study Approach

This report compiles the assumptions and methodologies used by BMcD during the study. Its purpose is to articulate the assumptions made to develop the deliverables and support ISO-NE in evaluating their existing rate structure and impacts to black start plants during a restoration event. The information presented in this study was developed using BMcD’s extensive knowledge and experience with black start facilities.

1.3 Statement of Limitations

Estimates and projections prepared by BMcD relating to performance, construction costs, and operating and maintenance costs are based on experience, qualifications, and judgment as a professional consultant. BMcD has no control over weather, cost and availability of labor, material and equipment, labor productivity, construction contractor's procedures and methods, unavoidable delays, construction contractor's method of determining prices, economic conditions, government regulations and laws (including interpretation thereof), competitive bidding and market conditions or other factors affecting such estimates or projections. Actual rates, costs, performance ratings, schedules, etc., may vary from the data provided.

2.0 STUDY BASIS AND ASSUMPTIONS

2.1 Scope Basis and Assumptions Matrix

Scope and economic assumptions used in developing the study are presented below.

2.2 General Assumptions

The assumptions below govern the overall approach of the study:

- All estimates are feasibility level estimates. Each option represents a generic site with the assumptions listed below. Site specific implications may affect these overall costs.
- Piling is excluded. Sites are assumed to be flat, with minimal rock and with soils suitable for spread footings.
- Project costs are shown based on an Engineer Procure and Construct (EPC) contract philosophy.
- All costs are presented as overnight costs in 2017$, escalation is excluded.
- Onsite infrastructures including raw water supply and electrical connection are available onsite.
- The multi-genset options assume that the new black start building can be sited 500 feet from the existing tie-ins. The single diesel generator options assume the generator can be sited 100 feet from existing tie-ins.
- Total project duration (start of engineering to commercial operation) is approximately 18 months for the multi-genset options and 14 months for the single generator options.
- Site prep costs include a new laydown area and a protected construction labor walkway from construction parking to the construction site.
- Caterpillar diesel generators were chosen as the representative starting sources for the black start generators.
- Diesel generators will include a belly tank with 24 hours of ultra-low sulfur diesel (ULSD) storage.
- Single diesel generators are located outdoors in the factory enclosure. Multiple diesel generators are located indoors in a heated building.
- Service water and compressed air services are not included in the heated building.
- A dry pipe sprinkler fire protection system is included in the generation building.
- For all options, the existing plant fire loop is extended to diesel generator area. The single engine options include a monitor for manual fire control.
- Diesel generator foundations include a slab that goes down to a frost depth of 4 feet.

- For controls, each diesel generator is provided with its own stand-alone control system. Control systems for single generators are connected to the existing plant DCS for remote monitoring and control. Multiple diesel generators are provided with a common master control system including a remote HMI for monitoring and control from the plant control room.
- Diesel generators for the 0-90 MVA options output power at 480 V. Diesel generators for the 90-300 MVA options output power at 4,160 V. Diesel generators for the 300+ MVA options output power at 6,900 V.
- For the static start engines, it is assumed that harmonics can be mitigated without the use of filters.
- Each option includes the conversion to allow isochronous or island mode operation for at least one gas turbine or hydroelectric generator (2x1 combined cycle options include two). At the same station additional gas turbines or hydroelectric generators can be converted at the cost of adding isochronous control. Adding isochronous control for a gas turbine is approximately $200k for controls work plus 25% for indirects and an additional 15% for EPC fees.
- The existing electrical system is assumed to have tie breakers such that any gas turbine or hydro unit can be started by the diesel generators through a single tie-in point in the existing electrical system.
- Diesel engines meet EPA Tier II emissions requirements. Post combustion emissions controls are assumed to be unnecessary since the engines are classified as emergency generators.
- Capital costs presented in this study do not include any profit that would be included with the black start rate.
- EPC contingency is included as 5% of the project costs and EPC fee is included as 8% of the project costs excluding owner costs.
- Owner's costs are included as 5% of the EPC costs.
- A 5% owners cost contingency is included on all EPC project costs and owner costs.
- Demolition or removal of hazardous materials is not included.
- Estimated schedule durations for multi-genset projects (included a generation building) are approximately 18 months from start of engineering to project completion. Single genset projects without a generation building are approximately 14 months.

2.3 EPC Project Indirect Costs

The following project indirect costs are included in capital cost estimates:

- Pre-operational testing, startup, startup management and calibration

- Construction/startup technical service
- Engineering and construction management
- Performance and payment bonds
- EPC fees & contingency

2.4 Owner Costs

Allowances for the following Owner's costs are included in the pricing estimates:

- Owner's Project Development
- Owner's Project Management
- Owner's Operational Personnel Prior to COD
- Owner's Legal Costs
- Owner's Start-up Engineering
- Operator Training
- Permitting and Licensing Fees
- Startup/Testing (Fuel & Consumables)
- Initial Fuel Inventory
- Operating Spare Parts
- Builders Risk Insurance
- Owner's Contingency

2.5 Cost Estimate Exclusions

The following costs are excluded from all estimates:

- Financing fees
- Interest during construction (IDC)
- Escalation
- Sales tax
- Transmission
- Water rights
- Off-site infrastructure
- Utility demand costs
- Energy consumed during testing for the battery and HVDC cost estimate
- Land
- Site Security

3.0 BLACK START CONVERSION

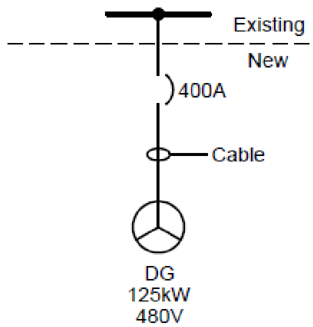
Depending on the existing generation plant size and configuration, the overall cost to add black start capabilities will vary. To quantify these varying costs, BMcD developed black start conversion estimates for various size generators and various plant configuration. The options evaluated are listed below.

- Hydro Plant
- <10 MVA - 1 x Wartsila 34DF Engine
- 10-60 MVA - 1 x Simple Cycle GE LM2500
- 60-90 MVA - 1 x Simple Cycle GE LM6000
- 90-300 MVA Small - 1 x Simple Cycle GE LMS100 or 2x1 Combined Cycle GE 7EA
- 90-300 MVA Medium - 2x1 Combined Cycle Siemens 501F
- 90-300 MVA Large - 1 x Simple Cycle GE 7FA.05 or 2x1 Combined Cycle GE 7FA.05
- 300+ MVA - 1 x Simple Cycle GE 7HA.02 or 2x1 Combined Cycle GE 7HA.02

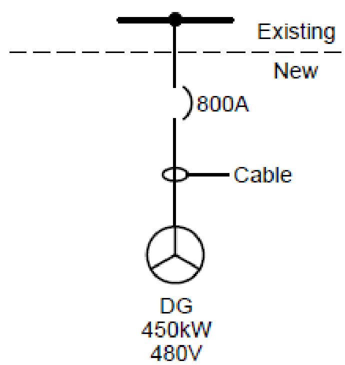
3.1 Black Start Option Descriptions

For each option, the number and size of diesel generators required will vary based on the starting requirements of the main plant. The descriptions below explain the electrical configuration for each option. For single generators, the main line travels from the diesel generator to a breaker at the tie-in to the existing switchgear. For multiple generators, a paralleling switchgear bus ties together all the individual diesel generators. A main breaker is positioned at this bus and at the tie-in point to the existing switchgear. It is assumed that the existing plant will have tie breakers so that any gas turbine at the plant could be black started through a single tie-in point at the existing switchgear. For large generating stations with two lineups of medium voltage switchgear, a new tie breaker and cable cross-tie have been included. The standard equipment listed below is included in the capital costs for each option.

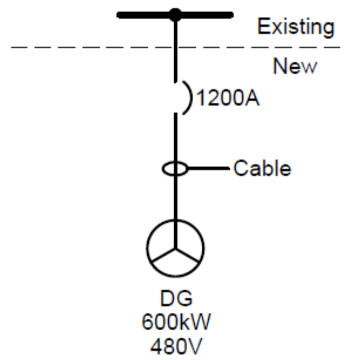
- Hydro Facility
    - One (1) Caterpillar 125kW (standby), 480V diesel generator prepackaged in a standalone enclosure.
    - One (1) 480V breaker to be added to the existing switchgear lineup.



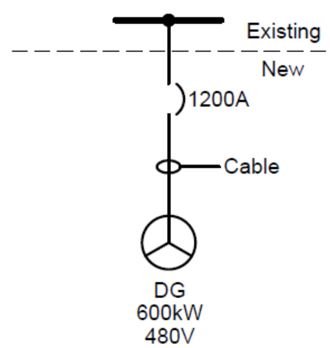
- <10 MVA Generator - 1 x Wartsila 34DF Engine
  - One (1) Caterpillar C15 ATAAC 450kW (standby), 480V diesel generator prepackaged in a standalone enclosure.
  - Wartsila services to modify engine controls for islanding and dead bus closure.
  - One (1) 480V breaker to be added to the existing switchgear lineup.



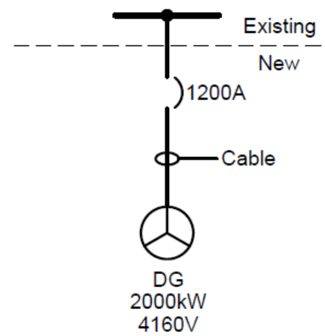
- 10-60 MVA Generator - 1 x Simple Cycle GE LM2500
  - One (1) Caterpillar C18 ATAAC 600kW (standby), 480V diesel generator prepackaged in a standalone enclosure.
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 480V breaker to be added to the existing switchgear lineup.



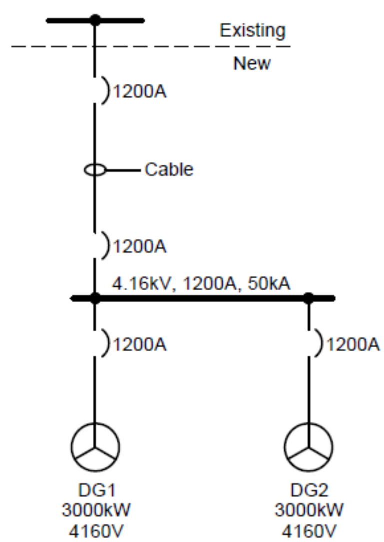
- 60-90 MVA Generator - 1 x Simple Cycle GE LM6000
  - One (1) Caterpillar C18 ATAAC 600kW (standby), 480V diesel generator prepackaged in a standalone enclosure.
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 480V breaker to be added to the existing switchgear lineup.



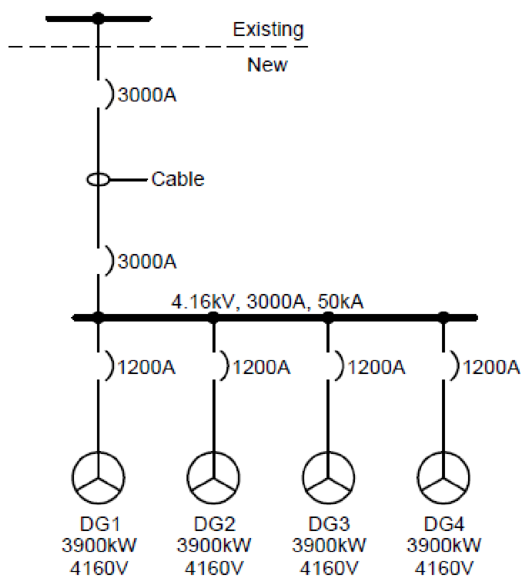
- 90-300 MVA Generator (small starting requirement Option 1) - 1 x Simple Cycle GE LMS100
  - One (1) Caterpillar 3516B 2000kW (standby), 4160V diesel generator prepackaged in a standalone enclosure.
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 4160V breaker to be added to the existing switchgear lineup.



- 90-300 MVA Generator (small starting requirement Option 2) - 2x1 Combined Cycle GE 7EA
    - Two (2) Caterpillar C175-16 3000kW (standby), 4160V diesel generators.
    - GE services to modify turbine controls for islanding and dead bus closure.
    - One (1) 5kV breaker to be added to the existing switchgear lineup.
    - A lineup of 5kV switchgear including two (2) diesel generator breakers and one (1) main breaker.
    - Diesel generator control system.
    - One (1) 400A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
    - Enclosure for new generators including HVAC and fire protection.

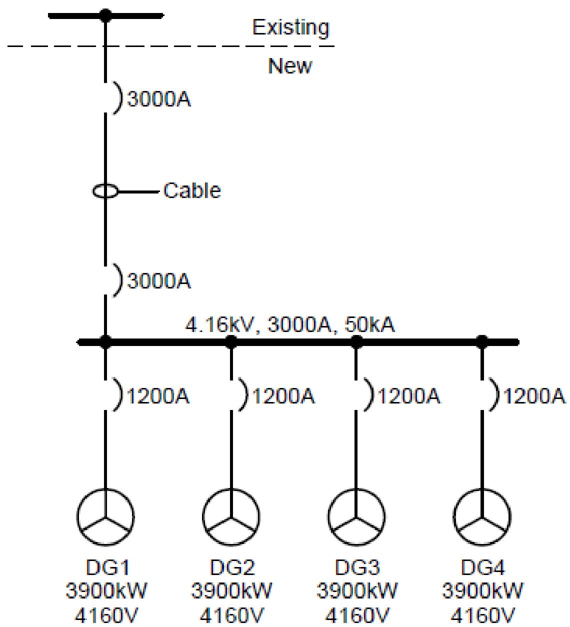


- 90-300 MVA Generator (medium starting requirement) - 2x1 Combined Cycle Siemens 501F
  - Four (4) Caterpillar C175-20 3900kW (standby), 4160V diesel generators
  - Siemens services to modify turbine controls for islanding and dead bus closure.
  - One (1) 5kV breaker to be added to the existing switchgear lineup and one (1) tie breaker.
  - A lineup of 5kV switchgear including four (4) diesel generator breakers and one (1) main breaker.
  - Diesel generator control system.
  - One (1) 600A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
  - Enclosure for new generators including HVAC and fire protection.



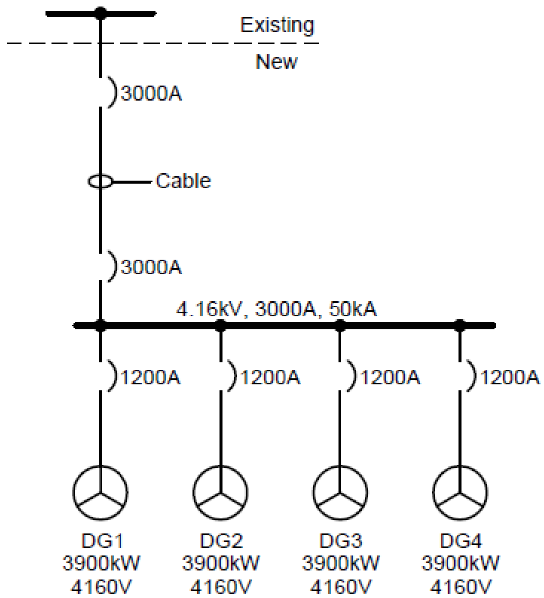
- 90-300 MVA Generator (large starting requirement Option 1) - 1 x Simple Cycle GE 7FA.05
  - Four (4) Caterpillar C175-20 3900kW (standby), 4160V diesel generators
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 5kV breaker to be added to the existing switchgear lineup and one (1) tie breaker.

- A lineup of 5kV switchgear including four (4) diesel generator breakers and one (1) main breaker.
- Diesel generator control system.
- One (1) 600A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
- Enclosure for new generators including HVAC and fire protection.

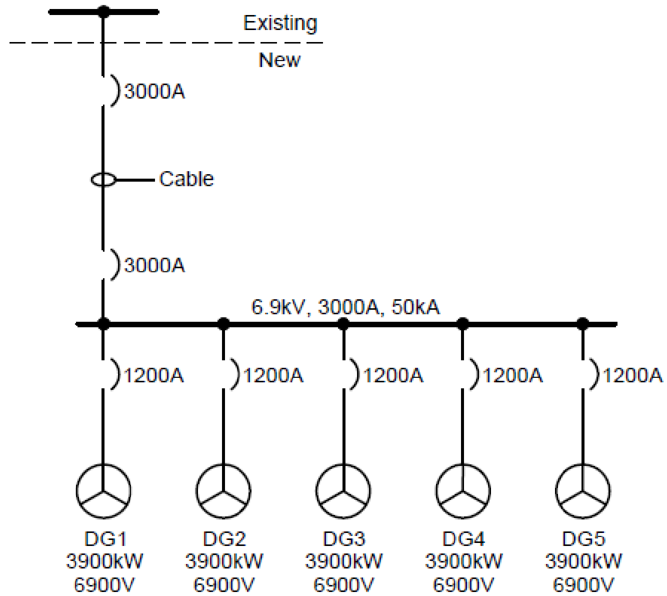


- 90-300 MVA Generator (large starting requirement Option 2) - 2x1 Combined Cycle GE 7FA.05
  - Four (4) Caterpillar C175-20 3900kW (standby), 4160V diesel generators
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 5kV breaker to be added to the existing switchgear lineup and one (1) tie breaker.
  - A lineup of 5kV switchgear including four (4) diesel generator breakers and one (1) main breaker.
  - Diesel generator control system.

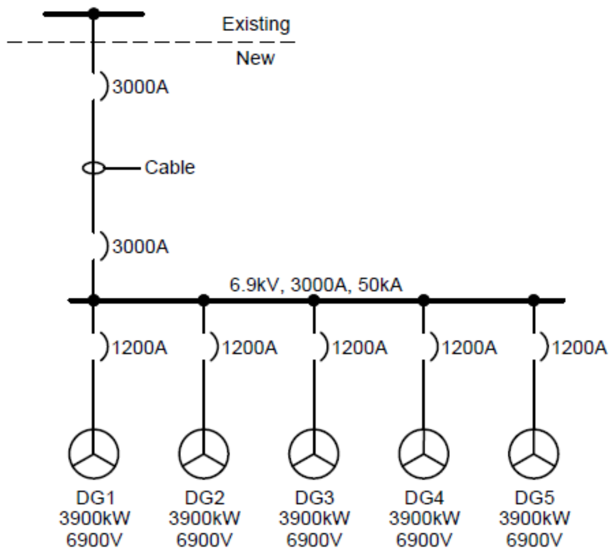
- One (1) 600A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
- Enclosure for new generators including HVAC and fire protection.



- >300 MVA Generator (large starting requirement Option 1) - 1 x Simple Cycle GE 7HA.02
  - Five (5) Caterpillar C175-20 3900kW (standby), 6900V diesel generators
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 15kV breaker to be added to the existing switchgear lineup and one (1) tie breaker.
  - A lineup of 15kV switchgear including five (5) diesel generator breakers and one (1) main breaker.
  - Diesel generator control system.
  - One (1) 600A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
  - Enclosure for new generators including HVAC and fire protection.



- >300 MVA Generator (large starting requirement Option 1) - 2x1 Combined Cycle GE 7HA.02
  - Five (5) Caterpillar C175-20 3900kW (standby), 6900V diesel generators
  - GE services to modify turbine controls for islanding and dead bus closure.
  - One (1) 15kV breaker to be added to the existing switchgear lineup and one (1) tie breaker.
  - A lineup of 15kV switchgear including five (5) diesel generator breakers and one (1) main breaker.
  - Diesel generator control system.
  - One (1) 600A, 480V power panel for diesel generator battery chargers, jacket water heaters, HVAC, etc.
  - Enclosure for new generators including HVAC and fire protection.



3.2 Diesel Generator Sizing Assumptions

Only the equipment required as a permissive to start the black start GTG will be in operation prior to starting the GTG. All other equipment will remain off until the GTG is started. The following are additional assumptions used in establishing what equipment is required as a permissive to start the black start GTG:

- Steam vent is included in the plant and adequately sized to allow steam venting to atmosphere with the GTG in operation so that the GTG can be started and operated in black start operating mode without the need to have the condenser and associated circulating water system in operation to accept a steam bypass.
- 2x50% boiler feed pumps per GTG included in the plant with only one boiler feed pump needed to start and synchronize the GTG.
- Condensate pumps do not need to be started as there is adequate water storage capacity in the deaerator or drum.
- No fuel gas compression is required prior to start and synchronize the GTG and bring the GTG up to a load adequate to facilitate operation of the compressors.
- Plant auxiliary cooling is assumed to be adequately available to support GTG start-up and synchronization without the need to start the main circulating water pumps.

- Control system running on essential service/batteries.
- Air compressors and other auxiliaries are not running.

In addition to sizing the diesel generators to mitigate harmonics issues associated with static starting systems, the diesel generators were sized to maintain 80% of rated voltage during starting of the largest motor. Caterpillar's online modeling software, Electric Power SpecSizer, was used to model the black start loads and calculate the voltage drop during starting of the largest motor.

3.3 Hydro General Description

Based on BMcD's experience with hydro units, little to no power is required for a black start. The hydro units are controlled by a series of gates that allows water to flow over the turbine. These are usually controlled by compressed air, hydraulic or electric motors, and typically also include manual operation. Since there is no main starting motor, a black start diesel generator is only need to run lube oil pumps, cooling water pumps, air compressors, and other small loads. Some hydro plants are equipped with a small hydro unit that provides black start auxiliary power, but this study assumes that all plants will be fitted with a diesel generator.

3.4 Reciprocating Engine General Description

The Wartsila 34DF was selected as the representative engine for the <10 MVA category. These engines typically utilize a compressed air starting system. The 34DF engine requires a 450 kW diesel generator to support water jacket heaters and other small auxiliary loads.

3.5 Gas Turbine General Description

To evaluate other generator sizes, this evaluation compares different classes of gas turbine equipment. Smaller aeroderivative engines, medium sized frame engines, and large frame engines were selected to represent the larger generator MVA categories.

The GE LM2500 was chosen for the 10-60 MVA category, the GE LM6000 for the 60-90 MVA category and the GE LMS100 for the 90-300 MVA Small category. These engines are taken from the aeronautical industry so they are designed for quick starts, durability, and are a very robust engine. These engines have a hydraulic motor that supplies cranking power for starts. The hydraulic motor has a 200 HP hydraulic pump for the LM2500, LM6000 and LMS100. The LM2500 and LM6000 require the same size diesel gensets but the LMS100 requires a larger 2 MW diesel genset due to its higher complexity and larger auxiliary loads of the cooling systems.

The GE 7EA was also chosen to represent the 90-300 MVA Small category. The 2x1 7EA combined cycle requires a larger starting generator due to the boiler feed pump and starting motor (both 1,000-1,500 HP) required for combined cycle operation. This option shows that even though the generator size is similar to the LMS100 engine, the starting requirement is higher due to the combined cycle configuration.

The Siemens 501F were selected to represent the 90-300 MVA Medium category. The 501F is started by a 2,200 HP starting motor and would typically have a 4,000+ boiler feed pump in combined cycle configuration. Due to the voltage drop of starting the large motors, over 15 MW of diesel gensets are required.

The GE 7FA was selected to represent the 90-300 MVA Large category and the GE 7HA was selected to represent the >300 MVA category. They are both large gas turbine engines that utilize a static starting system. Essentially the generator is used as a motor to start the gas turbine through the use of a load commutative inverter (LCI). The GE 7FA and GE 7HA generators require up to 7.1 MW and 9.7 MW respectively of auxiliary power to start the gas turbine. In addition, starting with such a large motor introduces harmonic issues in the system. These harmonics can be controlled with filters or additional generation can be added to make the system more stable. Filters are very large, costly, and can add additional problems. This study assumes that additional generation is added to stabilize the system. The 7FA and 7HA gas turbines require 15.6 MW and 19.5 MW respectively of diesel generators to support black start of the gas turbine and mitigate harmonic issues. Both gas turbines were evaluated in simple cycle and combined cycle configurations. Since the LCI is the driving factor for the diesel genset sizing, combined cycle or simple cycle configuration doesn't change the starting power requirement.

Large gas turbine engines that utilize a static starting system with fast acceleration dramatically increase the auxiliary power requirements. For example, a GE 7HA.02 equipped with a static starting system with fast acceleration requires up to 20.1 MW of auxiliary power to start the gas turbine compared to 9.7 MW for the same model gas turbine without fast acceleration. Due to the dramatic increase in auxiliary power requirements, large gas turbines equipped with static starting systems with fast acceleration are unlikely to be good candidates for black start conversion and were therefore excluded from the evaluation.

3.6 Black Start Emissions Controls and Permitting Review

Any diesel genset added to an existing site will be regulated under the New Source Performance Standards 40 CFR Part 60. These regulations specify varying levels of emission controls call Tiers. The higher the Tier the lower the emissions and more extensive emission control equipment. The diesel gensets will typically be required to meet Tier II emission requirements for an emergency facility. To further evaluate potential permitting and emission impacts, BMcD contacted the environmental department for each state in the ISO-NE territory. Each state is discussed below.

- Maine – The Maine Department of Environmental Protection (DEP) states that diesel generators of this size (Tier II emissions) being added to an existing Title V facility will be a Minor Modification, triggering a New Source Review. The Facility can request an operating limit of 100 hours for emission calculations. The timeline provided for their review is 3 to 6 months. The Facility needs to receive a License to Install before beginning construction, which would be issued after the DEPs review.

- Vermont – The Vermont Department of Environmental Conservation (DEC) requires the facility to apply for a Construction Permit for these generators. The potential to emit (PTE) for emergency generators is calculated at 200 hours, but a request for a limit of 100 hours can be made. Facilities would also need to ensure that the overall facility emissions for NOx don't exceed 100 tpy, as the state has no NOx allowances. 1-hour NOx modeling would be required. With the low operating hours of the diesel gensets, they will not exceed 100 tpy of NOx emissions.

- New Hampshire – The New Hampshire Department of Environmental Services (DES) requires that the PTE for emergency generators be calculated on a 500-hour basis. However, a request for a Federally Enforceable Limit of 100 hours of operation can be made. A Temporary Operating Permit (TOP, preconstruction permit) can be applied for with the 100-hours operation limit. This process usually takes 30 to 60 days.

- Rhode Island – The Rhode Island Department of Environmental Management (DEM) requires these generators to be permitted using the General Permit for Emergency Generators. A cover letter should be attached requesting the PTE to be calculated using 100 hours. The facility must receive a letter of approval for the General Permit from the DEM before the generators can be installed.

- Connecticut – These emergency generators are exempt from permitting under Section 22a-174-3b(e) of the Regulations of Connecticut State Agencies. The facility must notify the State that the facility elects to operate under a Permit-By-Rule regulation. The facility can begin construction after submitting the notification.

- Massachusetts – The Massachusetts DEP was contacted but they did not response. Preliminary review of public information shows that Tier II engines would applicable for emergency response.

3.7 Black Start Cost Estimates

This study provides information to facilitate ISO-NE's confirmation of their black start rate structure. Diesel generator system sizing, capital costs for black start conversion, and incremental O&M costs to operate the black start equipment and meet NERC requirements have been developed.

Estimated capital costs for the black start options can be found in Table 3-1 below. Further capital cost and detail can be found in Appendix A. The capital costs are based on the assumptions and equipment listed above in this report.

Table 3-1 – Black Start Capital Costs

	Hydro	Wartsilla	LM6000	LMS100	GE 7EA	Siemens 501F	GE 7FA	GE HA.02
Generator MVA	Hydro	10-60	60-90	90-300 Small	90-300 Small	90-300 Med	90-300 Large	>300
Diesel Gensets	1x125 kW	1x450kW	1x600kW	1x2,000kW	2x3,000kW	4x3,900kW	4x3,900kW	5x3,900kW
Direct and Indirect Costs	$ 1,249,839	$ 1,661,145	$ 1,756,939	$ 2,304,054	$ 11,223,051	$ 17,057,083	$ 17,057,083	$ 20,550,315
EPC Fees and Contingency	$ 167,478	$ 222,593	$ 235,430	$ 308,743	$ 1,503,889	$ 2,285,649	$ 2,285,649	$ 2,753,742
Total EPC Costs	$ 1,417,317	$ 1,883,739	$ 1,992,369	$ 2,612,797	$ 12,726,940	$ 19,342,732	$ 19,342,732	$ 23,304,058
Owner Costs	$ 145,275	$ 193,083	$ 204,218	$ 267,812	$ 1,304,511	$ 1,982,630	$ 1,982,630	$ 2,388,666
Total Project Costs	**$ 1,562,592**	**$ 2,076,822**	**$ 2,196,586**	**$ 2,880,609**	**$ 14,031,452**	**$ 21,325,362**	**$ 21,325,362**	**$ 25,692,723**

Based on the accuracy of the project costs and the accuracy of the scope outlined in this study, BMcD recommends utilizing a 5% contingency in the EPC costs and an overall contingency of 5% in the owner costs. The 5% EPC contingency is typical for power projects and is meant to cover pricing accuracy and labor productivity assumptions. The 5% owner contingency is included to further cover the estimate accuracy as well as small scope changes to the project. It is very typical for this level of contingency to represent "as spent" costs for EPC projects and would not considered to be excessive.

3.8 Black Start O&M

Estimated O&M costs for the black start options can be found in Table 3-2 below. The costs are presented in 2017$. It is assumed that no additional staffing will be dedicated to operating and maintaining the black start equipment. A portion of the O&M costs were developed by averaging the data from the black start questionnaires. This includes escalated data from 2011 as well as new data from the 2017 questionnaire. For each type of plant, some of the costs are independent of plant size and configuration. Record keeping, reporting, and communications testing are assumed to be the same for any sized facility. Property taxes and insurance were estimated as 2.0% and 0.25% of capital costs respectively.

Table 3-2 – Black Start O&M Costs

	Hydro	Wartsilla	LM6000	LMS100	GE 7EA	Siemens 501F	GE 7FA	GE HA.02	Notes
Generator MVA	Hydro	10-60	60-90	90-300 Small	90-300 Small	90-300 Med	90-300 Large	>300	
Configuration	Multi Unit Plant	1 x SCGT	1 x SCGT	1 x SCGT	2x1 CCGT	2x1 CCGT	2x1 CCGT	2x1 CCGT	
Black Start Testing Costs (Total annual costs including fuel and all O&M costs), $	$2,000	$3,000	$3,000	$3,000	$14,000	$19,000	$19,000	$27,000	BMcD estimate based on buildup of startup fuel usage and staffing.
Communications Testing	$1,300	$1,300	$1,300	$1,300	$1,300	$1,300	$1,300	$1,300	Average for all GT and Hydro plants, does not change with configuration
NERC Black Start Compliance Training (NERC EOP-005, required training every two years and drills, exercises, simulations requested by ISO/LCC)	$4,800	$4,800	$4,800	$4,800	$10,600	$10,600	$10,600	$10,600	For SC options, use average of SC survey results. CC options and hydro will be scaled up for staffing. Assumes 5 personnell will be trained for SC plant and 11 personnel for either a 1x1 or 2x1.
Other Black Start Training	$900	$900	$900	$900	$2,000	$2,000	$2,000	$2,000	For SC options, use average of SC survey results. CC options and hydro will be scaled up for staffing. Assumes 5 personnell will be trained for SC plant and 11 personnel for either a 1x1 or 2x1.
NERC Critical Infrastructure Protection (CIP) Requirements (please describe nature of CIP O&M)		See CIP Brekout in report.							BMcD estimate.
Record Keeping, Reporting and Other Administrative (not included above, please describe in notes)	$2,300	$2,300	$2,300	$2,300	$2,300	$2,300	$2,300	$2,300	Average of all survey resulst, GT and hydro.
Standby Power/Station Service Energy Costs	$5,600	$8,000	$8,700	$13,100	$40,500	$82,200	$85,900	$85,900	BMcD estimate.
Annual Equipment Inspection Costs, $	$1,100	$1,200	$1,300	$2,200	$5,500	$12,800	$12,800	$15,800	BMcD estimate based on information from Cat.
Routine Maintenance (Pump seals, lubrication, filters, oil changes, etc.), $	$700	$1,600	$1,900	$7,300	$15,300	$41,700	$41,700	$50,700	BMcD estimate based on information from Cat.
Black Start Equipment Property Taxes, $	$30,000	$42,000	$44,000	$58,000	$280,000	$426,000	$426,000	$514,000	2% of capital costs per ISO-NE from the Cost of New Entry Study. Calculated in Summary Sheet.
Black Start Equipment Insurance Costs, $	$4,000	$5,000	$6,000	$7,000	$35,000	$53,000	$53,000	$64,000	0.25% of capital costs based on typical values seen from other BMcD clients. Not necessarily specific to the New England area. Calculated in Summary Sheet
Total Annual Fixed O&M Costs, 2017$	**$52,700**	**$70,100**	**$74,200**	**$99,900**	**$406,500**	**$650,900**	**$654,600**	**$773,600**	

The O&M assumptions for each of the categories shown in Table 3-2 are discussed below.

- Black Start Testing Costs - BMcD developed costs based on estimated staffing and fuel usage for a black start test. One CT for each option is assumed to be tested. The CT will be started and held at approximately 5% load for 10 minutes. It is assumed that the unit will not be synced to the grid but must be held at 5% to support house loads. For the combined cycle options, the steam turbine will not be synced and any steam will be dumped to the condenser or atmosphere. The simple cycle/hydro options include 5 personnel for 4 hours and the combined cycle options include 11 personnel for 4 hours. Fuel, variable O&M, and major maintenance cost is included for the testing duration.

- Communications Testing - Communications testing costs are based on the average generator survey results for both combustion turbine and hydro plants. These costs are assumed to be the same for each option.

- NERC Black Start Compliance Training - Compliance training is based on the generator survey results. The results for the simple cycle plants have been averaged and are used for the simple cycle/hydro options in this report. It is assumed that compliance testing will vary based on the number of personnel trained. The average simple cycle training cost was scaled directly for personnel. It is assumed that 5 personnel are trained for the simple cycle plants and 11 personnel are trained for the combined cycle plants.

- Other Black Start Training - Other training cost was developed similarly to the compliance training line item. The average of the simple cycle generator survey results was used for the simple cycle/hydro options and this was scaled for the combined cycle units using the same personnel assumptions.

- Record Keeping, Reporting, And Other Administrative - Administrative costs are based on the average generator survey results for both combustion turbine and hydro plants. These costs are assumed to be the same for each option.

- Standby Power/Station Service Energy Costs - BMcD developed an estimate of station service loads specifically related to the black start equipment. Loads include HVAC for the options that include an enclosure, lighting, and battery chargers.

- Annual Equipment Inspection Costs - BMcD developed an estimate of inspection costs specifically related to the black start equipment. The diesel generators are typically load tested every year. Costs include one technician for a full day and four hours of diesel fuel for each diesel generator.

- Routine Maintenance Costs - BMcD developed an estimate of maintenance costs specifically related to the black start equipment. Costs include a typical oil change twice a year and diesel generator exercising for one hour each month. The exercises are fully automatic so no labor is included.

- Black Start Equipment Property Taxes - Property taxes are included at 2.0% of the capital costs. This property tax rate is based on information from generators in the New England area.

- Black Start Equipment Insurance - Insurance costs are included at 0.25% of the capital costs. The insurance rate is based typical values from other BMcD studies.

- NERC Critical Infrastructure Protection - CIP costs are not presented in this section but are presented in Section 3.9 below.

3.9 NERC Critical Infrastructure Protection

If a generator adds black start capability at their facility and becomes part of the ISO-NE restoration plan, the facility may become a critical asset under current rules. In addition, NERC has proposed that all generators in a restoration plan are critical assets. As a critical asset, the plant must now meet the NERC Critical Asset Protection (CIP) guidelines. Depending on the nature of assets present, various forms of physical and cyber-security may need to be added such as fencing, gates, card readers, video surveillance, and software modifications.

The NERC CIP guidelines are constantly changing. An operating plant is referred to as a Bulk Electric System (BES) Cyber System. Based on current regulations, BES Cyber Systems not categorized in high impact or medium impact default to low impact. A low impact plant requires less security systems. NERC only recently allowed black start plants to fall under low impact. Below describes how the CIP regulations have changed.

Several discussions on the CIP Version 5 standards suggest entities owning Blackstart Resources and Cranking Paths might elect to remove those services to avoid higher compliance costs. For example, one

Reliability Coordinator reported a 25% reduction of Blackstart Resources as a result of the Version 1 language, and there could be more entities that make this choice under Version 5.

In response, the CIP Version 5 drafting team sought informal input from NERC's Operating and Planning Committees. The committees indicate there has already been a reduction in Blackstart Resources because of increased CIP compliance costs, environmental rules, and other risks; continued inclusion within Version 5 at a category that would very significantly increase compliance costs can result in further reduction of a vulnerable pool.

The drafting team moved from the categorization of restoration assets such as Blackstart Resources and Cranking Paths as medium impact (as was the case in earlier drafts) to categorization of these assets as low impact as a result of these considerations. This will not relieve asset owners of all responsibilities, as would have been the case in CIP-002,Versions 1-4 (since only Cyber Assets with routable connectivity which are essential to restoration assets are included in those versions). Under the low impact categorization, those assets will be protected in the areas of cyber security awareness, physical access control, and electronic access control, and they will have obligations regarding incident response. This represents a net gain to bulk power system reliability, however, since many of those assets do not meet criteria for inclusion under Versions 1-4.

Weighing the risks to overall BES reliability, the drafting team determined that this recategorization represents the option that would be the least detrimental to restoration function and, thus, overall BES reliability. Removing Blackstart Resources and Cranking Paths from medium impact promotes overall reliability, as the likely alternative is fewer Blackstart Resources supporting timely restoration when needed.

Based on these recent changes, current NERC CIP low impact retrofit costs are shown in Table 3-3 below.

Table 3-3 – NERC CIP Low Impact Costs

Plant Configuration	Generator MVA	Physical Security (CIP-004 & CIP-006)		Cyber Security (CIP-003 - CIP-009)	
		Capital Costs, 2017$	O&M Costs, 2017$/yr	Capital Costs, 2017$	O&M Costs, 2017$/yr
HVDC-VSC	HVDC-VSC	$336,400	$150,900	$24,200	$88,000
Hydro	Hydro	$336,400	$150,900	$24,200	$88,000
Wartsila	10-60	$336,400	$150,900	$24,200	$88,000
LM6000	60-90	$336,400	$150,900	$24,200	$88,000
LMS100	90-300 Small	$336,400	$150,900	$24,200	$88,000
GE 7EA	90-300 Small	$376,800	$160,000	$25,700	$93,300
Siemens 501F	90-300 Med	$403,700	$173,500	$28,600	$101,200
GE 7FA	90-300 Large	$403,700	$173,500	$28,600	$101,200
GE HA.02	>300	$417,100	$178,100	$29,000	$103,800

4.0 VSC-HVDC

To improve the effectiveness and reliability of system restoration plans, modern power systems require advanced black-start solutions. Utilizing the quick and reliable starting of HVDC links can coordinate well with the robust restoration and operation of the a.c. power network. This Section provides a high-level overview of voltage source converter (VSC) technology and its application for black-start restoration process. This Section also discusses on several significant VSC control functions for black start operation. Additionally, estimates for a 300-MW/1200-MW VSC-HVDC system and a supplemental black-start retrofit costs are is also provided.

4.1 HVDC Technology And Black-Start Capability

High Voltage DC (HVDC) system offers black-start resources as utilized in the world's first commercial HVDC project, built in 1954, the 20 MW, 100 kV Gotland-1 HVDC link. Gotland-1 converters originally used line-commutated mercury-arc valves, replaced by thyristors valves in 1970, had black-start capability. To start-up the d.c. system with a dead receiving network, the HVDC stations used line-commutated converters (LCCs) and synchronous condensers, but this complicated the start-up sequence during power system restoration. Alternatively, the introduction of voltage-sourced converters (VSCs) in the late 1980s, with ratings suitable for transmission, has simplified black-start sequence. Synchronous condensers are not required for operation or for starting VSC-based HVDC transmission system.

VSC technology has numerous benefits over classical HVDC (LCC). VSC technology has broadened HVDC application base for use in relatively weak systems, as an outlet for non-traditional renewable generation (i.e., wind power), and for long underground connections with extruded cables. Operation with weaker a.c. system interconnection is possible due to the improved voltage stability with VSCs. VSC systems can better ride through under voltage swings while reducing their severity by providing dynamic voltage support. VSCs are self-commutated and can operate indefinitely at zero-power or very low-power transfers. VSCs can control reactive power and active power independently and can act as a virtual generator in a network that otherwise lacks generation. Another important aspect of a VSC system is the ability to change power direction without voltage reversal. These distinct capabilities enable VSC systems as a vital component of the power restoration process during black start.

4.2 VSC-Based HVDC Black Start

A VSC-based HVDC system can only perform black start if this control feature is incorporated to the VSC system design. As stated, a LCC-HVDC converter controls do not support black start without a synchronous condenser. A black-start procedure can be initiated when a VSC converter is started and connected to a black a.c. network. The needed power is supplied from a remote converter station. The auxiliary power for the VSC terminal is required and can be supplied either by a diesel generator or by a battery back-up to carry forward islanded network operation.

A black start is the act of energizing a dead a.c. busbar and supplying an a.c. system with power from the remote end of the VSC-HVDC link, where the converter in the islanded grid is controlling the a.c. voltage and frequency and acting as a stiff voltage source. A black start sequence is project specific and different among VSC-HVDC manufacturers.

During black start, the following VSC-HVDC control functions are generally used:

- Islanded network/black start control
- STATCOM mode
- DC Voltage control
- AC Voltage control
- Reactive power control
- Frequency control

4.2.1 Islanded Network/Black Start Control

Islanded mode is defined when one converter terminal of a VSC-HVDC scheme being connected to a limited segment of a.c. network that is not connected to a larger integrated a.c. network. This could be by design i.e. where a HVDC converter terminal supplies a small, isolated a.c. network, or it can occur when a limited section of an a.c. network has become separated from a larger a.c. network to which it is normally connected. The converter at one end is connected via HVDC link to another VSC converter which is connected to an islanded a.c. network. The converter connected to the islanded network can control its a.c. voltage and frequency.

The islanded network may or may not contain sources of generation. When an islanded network separates from a larger a.c. network there may be a surplus or deficit of generation in the network. The HVDC scheme can assist with keeping the islanded network stable by supplying power to or removing power from the islanded network. This assumes that the other converter terminal is connected to a healthy a.c. network and can provide/absorb the balance of power supplies.

An islanded operation is achieved by the HVDC system providing frequency control of the islanded network. Converters can provide stable frequency support to islanded or passive networks, and also robust voltage support when inherent voltage collapse situations arise thereby preventing eventual blackout of the islanded/passive networks. The islanded network operation mode is necessary for black start of a network or when the HVDC link is connected to an islanded network where no other frequency controller is available.

4.2.2 STATCOM Mode

STATCOM is the mode of operation of a VSC converter when only reactive power (capacitive or inductive) is exchanged with the a.c. system. The HVDC link can either be connected or disconnected from the converter station. If connected, the active power order shall be equal to zero.

In this mode, the VSC converter is deblocked and fully energized from the a.c. side but the d.c. side is either isolated or configured such that no active power is transmitted. The reactive power can be controlled at the converter's a.c. side and the d.c. bus voltage can be controlled.

4.2.3 DC Voltage Control

Under normal operating condition, one VSC converter can operate in active power control mode, the other can be set and hold the d.c. voltage at a specific level. The d.c. voltage control sets the d.c. voltage at one end of the VSC system to a specified d.c. voltage level, which allows the other converter in active power control to cause power to flow on the d.c. side by adjusting its own d.c. voltage relative to the specified d.c. voltage at the other end. The d.c. voltage control forces the d.c. terminal voltage to track the reference setting and the control action results in an active current order. During black starts, both VSC converters will be in operation and follow necessary controls depending on the status of the connected a.c. network (whether live or dead bus).

4.2.4 AC Voltage Control

AC voltage control regulates the flow of reactive power to or from the converter to achieve an a.c. voltage level defined by a setpoint provided by the operator. This is achieved by regulating the magnitude of the fundamental frequency component of the a.c. voltage generated at the VSC side of the interface reactor and/or transformer.

If the VSC system feeds into an isolated a.c. system with no other significant form of active power source, the a.c. voltage controller will automatically control power to the load during the restoration process while the other converter terminal will control the d.c. side voltage independently.

4.2.5 Reactive Power Control

The VSC-HVDC converters can either generate or consume reactive power. This is done independently of the other converters in the scheme and independently of the active power transfer, within the bounds of the converter's PQ characteristic. This is achieved by the converter adjusting its internal voltage until the desired reactive power exchange is equal to the requested setpoint values. Once a reactive power control setpoint is entered, the converter will absorb or generate that amount of reactive power independent of voltage variations in the a.c. network.

4.2.6 Frequency Control

Frequency control where the VSC system is sharing in the control of the a.c. system frequency, is commonly applied in the form of a slope characteristic, where power flow through the converter is controlled dynamically in magnitude and direction to maintain constant a.c. system frequency. The ability of the VSC-HVDC converter to have an influence on the a.c. system frequency is clearly dependent on the relative capacities of the a.c. system and the VSC-HVDC terminal.

Passive or islanded a.c. network conditions are detected by frequency deviation criteria and the converter terminal connected to the passive/islanded network will be transferred from active power control or d.c. voltage control to frequency control. The sending end converter terminal will need to be connected to a normal, healthy a.c. network that can supply the passive network or provide the balance of power required in the islanded network at the receiving end. In the unlikely event that the a.c. networks at both ends of the HVDC scheme become islanded or passive the HVDC scheme will be tripped as unstable operating conditions occur on both sides of the HVDC system.

4.3 Capital Costs - New VSC-HVDC Terminal

HVDC terminals are custom engineered facilities delivered by major VSC-HVDC equipment manufacturers or vendors, e.g., ABB, Siemens, GE (formally Alstom) or Mitsubishi. A typical cost of a 300-MW VSC-HVDC system is about $120MM to $160MM plus $3.5MM per mile of the HVDC transmission line, which varies among different OEMs (original equipment manufacturers). For terminal capacity upgrades, an incremental cost of $380/kW is estimated for capacity increase from 301 MW to 1200MW. To include black start capability in a new VSC-HVDC terminal, , the added cost should be less than $100k or essentially free (included in cost of facility).

4.4 Capital Costs – Retrofit Existing VSC-HVDC Facility

A utility may prefer black-starts retrofit upgrade if a VSC-HVDC terminal is located nearby a power plant or adjacent to power transmission network. If the VSC system lacks black-starts control, an additional cost is needed to upgrade the VSC control systems. To incorporate black-starts control features to existing VSC control systems, the following studies and testing are to be required:

- Power system studies (including dynamic study as applicable)
- Control & protection system design upgrade
- Testing (FAT or RTDS) and commissioning of black starts control modules (as applicable).

Based on input from ABB, approximately $1-1.5MM is estimated for the back-starts retrofit upgrade. This was considered a very conservative cost that could vary depending on the existing facility. Upgrade costs could range from less than $100,000 up to the $1.5MM value suggested by ABB depending on type and age of facility and existing hardware. Without a detailed evaluation of the specific facility, it is impossible to estimate the exact cost. They noted that this should not add any additional O&M costs for operation of the VSC-HVDC facility.

5.0 STORAGE TECHNOLOGY

Electrochemical energy storage systems utilize chemical reactions within a battery cell to facilitate electron flow, converting electrical energy to chemical energy when charging and generating an electric current when discharged. Electrochemical technology is continually developing as one of the leading energy storage and load following technologies due to its modularity, ease of installation and operation, and relative design maturity. Development of electrochemical batteries has shifted into three categories, commonly termed “flow,” “conventional,” and “high temperature” battery designs. Each battery type has unique features yielding specific advantages compared to one another.

5.1.1 Flow Batteries

Flow batteries utilize an electrode cell stack with externally stored electrolyte material. The flow battery is comprised of positive and negative electrode cell stacks separated by a selectively permeable ion exchange membrane, in which the charge-inducing chemical reaction occurs, and liquid electrolyte storage tanks, which hold the stored energy until discharge is required. Various control and pumped circulation systems complete the flow battery system in which the cells can be stacked in series to achieve the desired voltage difference.

The battery is charged as the liquid electrolytes are pumped through the electrode cell stacks, which serve only as a catalyst and transport medium to the ion-inducing chemical reaction. The excess positive ions at the anode are allowed through the ion-selective membrane to maintain electroneutrality at the cathode, which experiences a buildup of negative ions. The charged electrolyte solution is circulated back to storage tanks until the process is allowed to repeat in reverse for discharge as necessary.

In addition to external electrolyte storage, flow batteries differ from traditional batteries in that energy conversion occurs as a direct result of the reduction-oxidation reactions occurring in the electrolyte solution itself. The electrode is not a component of the electrochemical fuel and does not participate in the chemical reaction. Therefore, the electrodes are not subject to the same deterioration that depletes electrical performance of traditional batteries, resulting in high cycling life of the flow battery. Flow batteries are also scalable such that energy storage capacity is determined by the size of the electrolyte storage tanks, allowing the system to approach its theoretical energy density. Flow batteries are typically less capital intensive than some conventional batteries but require additional installation and operation costs associated with balance of plant equipment.

For the purposes of generation black-start, the flow battery technology does not provide the high power requirements needed to address the in-rush of loads at the plant during start-up. For grid black-start purposes, where approximately 2 hours of discharge are needed, it is unlikely the flow battery pricing will be competitive with other technologies since the technology is designed to provide 4+ hour discharge durations.

5.1.2 "Conventional" Batteries

A conventional battery contains a cathodic and an anodic electrode and an electrolyte sealed within a cell container than can be connected in series to increase overall facility storage and output. During charging, the electrolyte is ionized such that when discharged, a reduction-oxidation reaction occurs, which forces electrons to migrate from the anode to the cathode thereby generating electric current. Batteries are designated by the electrochemicals utilized within the cell; the most popular conventional batteries are lead acid and lithium ion type batteries.

Lead acid batteries are the most mature and commercially accessible battery technology, as their design has undergone considerable development since conceptualized in the late 1800s. The Department of Energy (DOE) estimates there is approximately 110 MW of lead acid battery storage currently installed worldwide. Although lead acid batteries require relatively low capital cost, this technology also has inherently high maintenance costs and handling issues associated with toxicity, as well as low energy density (yields higher land and civil work requirements). Lead acid batteries also have a relatively short life cycle at 5 to 10 years, especially when used in high cycling applications.

Lithium ion (Li-ion) batteries contain graphite and metal-oxide electrodes and lithium ions dissolved within an organic electrolyte. The movement of lithium ions during cell charge and discharge generates current. Li-ion technology has seen a resurgence of development in recent years due to its high energy density, low self-discharge, and cycling tolerance. The life cycle of Li-ion batteries can range from 2,000 to 3,000 cycles (at high discharge rates) up to 7,000 cycles (at very low discharge rates). Many Li-ion manufacturers currently offer 5-15 year warranties or performance guarantees. Consequently, Li- ion has gained traction in several markets including the utility and automotive industries. The DOE estimates there is now approximately 1,240 MW of Li-ion battery storage installed worldwide.

Li-ion battery prices are trending downward, and continued development and investment by manufacturers are expected to further reduce production costs. While there is still a wide range of project cost expectations due to market uncertainty, Li-ion batteries are anticipated to expand their reach in the utility market sector.

For the purposes of generation black-start, lithium ion and lead-acid batteries are capable of providing the high power needed for in-rush of loads at the plant during start-up and are getting close to price parity with traditional diesel generators for this purpose only. However, neither technology is price competitive with traditional diesel generators when these batteries must provide plant auxiliary power in the event that the generator is not called up by the ISO for any longer than 1 hour after the grid outage occurs. Since this is likely to occur during most outages, the use of lithium ion or lead acid batteries for the sole purpose of black-start is not ideal. An alternative to this would be the installation of a smaller diesel generator to support extended auxiliary loads and to have the battery provide the high power needed during start-up. The pricing for this system would be much higher than providing a single diesel generator, but the use of the battery for other purposes such as frequency regulation, plant turn-down, spinning reserves, etc. could provide additional revenues. However, due to the critical need of black-start capacity during a grid level outage, ISO-NE should not allow for the operation of a battery asset for other purposes; this in turn makes a traditional diesel generator more favorable.

For grid black-start purposes, where approximately 2 hours of discharge are needed, lithium-ion batteries are well suited to provide this duration at a reasonable cost compared to other battery technologies. However, a developer or utility should not install lithium-ion solely for the purpose of black-start since the economics would not be favorable. It would be optimal to use the batteries primarily as supply capacity, frequency regulation, and other grid services. However, as noted previously, due to the critical need of black-start capacity during a grid level outage, ISO-NE should not allow for the operation of a battery asset for other purposes; which in turn makes a traditional diesel generator more favorable.

5.1.3 High Temperature Batteries

High temperature batteries operate similarly to conventional batteries, but utilize molten salt electrodes and carry the added advantage that high temperature operation can yield heat for other applications simultaneously. The technology is considered mature with ongoing commercial development at the grid level. The most popular and technically developed high temperature option is the Sodium Sulfur (NaS) battery. Japan-based NGK Insulators, the largest NaS battery manufacturer, recently installed a 4 MW system in Presidio, Texas in 2010 following operation of systems totaling more than 160 MW since the project’s inception in the 1980s.

The NaS battery is typically a hermetically sealed cell that consists of a molten sulfur electrolyte at the cathode and molten sodium electrolyte at the anode, separated by a Beta-alumina ceramic membrane and enclosed in an aluminum casing. The membrane is selectively permeable only to positive sodium ions, which are created from the oxidation of sodium metal and pass through to combine with sulfur resulting in the formation of sodium polysulfides. As power is supplied to the battery in charging, the sodium ions are dissociated from the polysulfides and forced back through the membrane to re-form elemental sodium. The melting points of sodium and sulfur are approximately 98ºC and 113ºC, respectively. To maintain the electrolytes in liquid form and for optimal performance, the NaS battery systems are typically operated and stored at around 300ºC, which results in a higher self-discharge rate of 14 percent to 18 percent. For this reason, these systems are usually designed for use in high-cycling applications and longer discharge durations.

NaS systems are expected to have an operable life of around 15 years, and are one of the most developed chemical energy storage technologies. However, unlike other battery types, costs of NaS systems have historically held, making other options more commercially viable at present.

For the purposes of generation black-start, the NaS technology does not provide the high power requirements needed to address the in-rush of loads at the plant during start-up. For grid black-start purposes, where approximately 2 hours of discharge are needed, it is unlikely the NaS pricing will be competitive with other technologies since the technology is designed to provide 6-8 hour discharge durations.

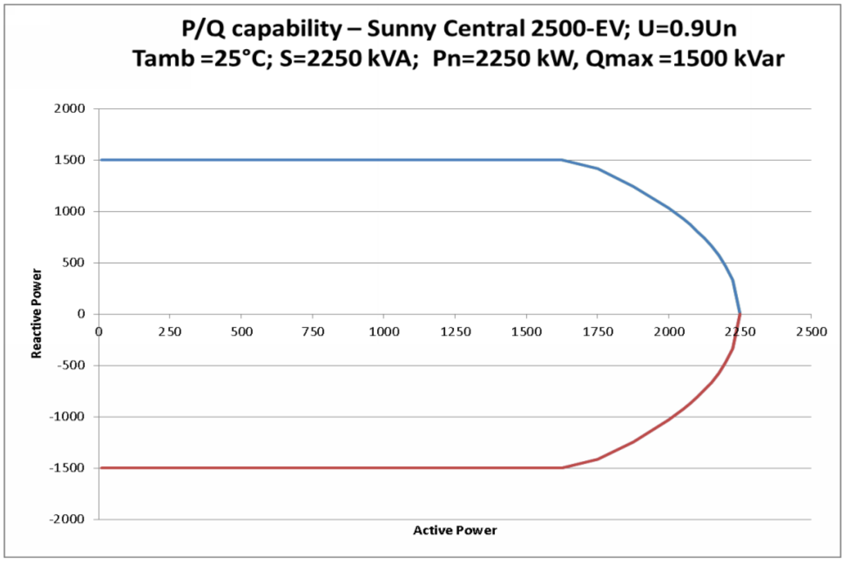
5.2 Battery Emissions Controls

No emission controls are currently required for battery storage facilities. However, lead acid batteries may produce hydrogen off-gassing via electrolysis when charging. Additionally, Li-ion batteries can release large amounts of gas during a fire event. While not currently an issue, there is potential for increased scrutiny as more battery systems are placed into service.

5.3 Battery Storage Performance

This assessment includes performance of a 100 MW/200 MWh grid-tied system and a 15.5 MW / 8.5 MWh gen-tied system, based on Li-ion batteries. Lithium ion systems can respond in seconds and exhibit excellent ramp rates and round trip cycle efficiencies. Because the technology is still maturing, there is uncertainty regarding estimates for cycle life, and these estimates vary greatly depending on the application and depth of discharge. The systems in this Assessment are assumed to perform only once per year.

For a grid-tied battery, the size of 100 MW / 200 MWh was chosen to best match the type of black start asset needed for the ISO NE grid. A minimum run time of two hours is needed to support the grid during start up. Depending on the inverter manufacturer, a 100MW battery system can source or absorb approximately 66% or more of the rated capacity (66 MVAR) as shown in the example reactive power curve below.



Example 1 - Inverter Reactive Power Curve

For a gen-tied battery, the size of 15.5 MW / 8.5 MWh was chosen as a comparison to a 2 MW diesel generator being used for black start of a 155MW GE LMS100. The same start up load profile was used, however, the sizing of the battery does not include extended run-times for auxiliary loads that may be needed if the LMS100 is not called upon by ISO NE for any more than 1 hour after the grid outage. In this scenario, a smaller generator would be needed in addition to the battery to support these extended auxiliary loads; this cost was not considered since the magnitude of battery cost is already well beyond that of a diesel generator. Additionally, the need for a much higher power output of the battery compared to the diesel is due to the inverter and batteries inability to source additional in-rush current for motor loads. Therefore, the system must be oversized as compared to the nominal load of the system.

5.4 Battery Storage Cost Estimate

The estimated cost of the lithium ion battery systems is included in the table below, based on BMcD experience and industry research. The key cost elements of a battery system are the inverter, the battery cells, the enclosure, and the software. The capital costs reflect an overbuilt battery capacity to account for normal degradation over time and limited failures. This ensures the net capacity remains the same over the life of the project. It is assumed that the system will be co-located with an existing asset so interconnection costs are excluded. It is assumed that the system will operate at 480V with a 230kV step-up transformer for the grid-tied system. Material costs are only included here since the construction costs between a battery and diesel generator will be similar due to their “modular” designs.

Table 5-1 - Estimated BESS Pricing

Application	BESS Size	Estimated Cost	Comparison Cost
Grid-Tied Black Start	100 MW / 200 MWh	$85M [1] (Total Installed Cost)	
Gen-Tied Black Start	15.5 MW / 8.5 MWh	$5.6M (Equipment Only)	$2.9M [2]

1 – Extremely high cost for an asset that can only be used in a black start scenario.
2 – As compared to all in cost, furnish and erect 2MW diesel generator with matching black start load profile.

6.0 BLACK START RISK STUDY

Burns and McDonnell performed a review of black start operations and subsequent system restoration to evaluate potential risks to plant equipment due to abnormal operating conditions. The following abnormal operating conditions were identified and evaluated:

- High Voltages - The black start and system restoration process could produce high generator voltages; however, existing generator protection over-voltage elements (59) and volts per hertz elements (24) should adequately protect plant equipment. No risk to equipment is expected.

- Low Voltages - The black start and system restoration process could produce low generator voltages. Low voltages are not harmful to equipment; however, low voltages could cause auxiliary power system equipment to experience over-currents. Existing over-current protection elements (51) on motor, bus and transformer feeders should adequately protect auxiliary power system equipment. No risk to equipment is expected.

- High Frequency - The black start and system restoration process could produce high generator frequencies; however, existing generator protection over-frequency elements (81O) should adequately protect plant equipment. No risk to equipment is expected.

- Low Frequency - The black start and system restoration process could produce low generator frequencies; however, existing generator protection under-frequency elements (81U) should adequately protect plant equipment. No risk to equipment is expected.

- System Ground Faults - The black start and system restoration process could expose the generator to system ground fault currents; however, existing generator protection negative sequence over-current elements (46) and/or backup distance elements (21) should adequately protect plant equipment. No risk to equipment is expected.

- System Phase Faults - The black start and system restoration process could expose the generator to system phase fault currents; however, existing generator protection backup distance elements (21) should adequately protect plant equipment. No risk to equipment is expected.

- Droop/Isochronous Switching - The black start and system restoration process could produce power swings between multiple generators if more than one generator is operated in isochronous mode. A system restoration plan should be developed to facilitate communications between all parties to avoid multiple isochronous units and excessive power swings. If a power swing exceeds the capability of a turbine-generator, it will trip off line and delay the system restoration process; however, no risk to equipment is expected.

Burns and McDonnell did not identify any risks to plant equipment due to black start operations and subsequent system restoration. Existing protection should provide adequate protection.

To avoid abnormal operating conditions that could trip one or more units off line, a system restoration plan should be developed that considers the turbine-generator loading limitations. For example, GE has specified for the 7FA.05 gas turbine that the magnitude of load block addition must not exceed 2.5% of rated base load capacity depending upon ambient conditions. These limits will need to be maintained to avoid abnormal conditions that could operate protective relays.

7.0 CONCLUSIONS

ISO-NE should use the capital costs and O&M costs presented in this report to evaluate their current black start rate structure. Compared to the 2011 report previously performed by BMcD, capital costs have increased significantly since 2011. Part of this increase is due to general market increases and diesel genset costs, but BMcD also adjusted the scope of each option based on our continued development of black start projects. The information presented in this report is based on a generic Brownfield site. Other than the assumptions listed in this report, site specific implications have not been considered. The information will allow ISO-NE to develop a rate structure for their black start program.

Battery storage options are not an economically viable option for black start plants. They are more expensive than traditional diesel genset applications and they would be under-utilized if only allowed to operate during a black start scenario.

BMcD also evaluated VSC based HVDC systems to support a restoration event. An VSC-HVDC system can provide dynamic voltage support, controllability, and ability to connect asynchronously to adjacent grids or with intact islands within the larger power system. VSC controls can offer system operators additional flexibility during power grid restoration. Black-start capability can be implemented in a new facility or an existing facility for relatively low cost.

BMcD also evaluated potential risks of a black start plant during a restoration event. Assuming that the existing plant is well maintained and includes standard protections as discussed in this study, a black start facility is at low risk of being damaged due to grid instability.

APPENDIX A - PROJECT COST SUMMARIES

CAPITAL COST ESTIMATE
ISO NEW ENGLAND
BLACK START STUDY
101421
NEW ENGLAND AREA

		Hydro	10-60	60-90	90-300 Small	90-300 Small	90-300 Medium	90-300 Large	>300
		125 kW - 1 ENGINE	450 kW - 1 ENGINE	600 kW - 1 ENGINE	2,000 kW - 1 ENGINE	6,000 kW - 2 ENGINE	15,600 kW - 4 ENGINE	15,600 kW - 4 ENGINE	19,500 kW - 5 ENGINE
Acct	**Area / Discipline**	**Total Cost**	**Total Cost**	**Total Cost**	**Total Cost**	**Total Cost**	**Total Cost**	**Total Cost**	**Total Cost**
01.1	Engine Supply	$50,000	$105,672	$182,250	$726,750	$2,995,000	$6,395,000	$6,395,000	$8,190,000
01.2	Elec & BOP Equipment Supply	$195,000	$488,480	$488,480	$488,480	$463,480	$573,480	$573,480	$585,980
01.3	Equipment Installation	$43,297	$43,297	$43,297	$43,297	$115,276	$208,804	$208,804	$298,311
02	Civil	$193,387	$193,387	$193,387	$193,387	$1,322,010	$1,325,151	$1,325,151	$1,406,177
04	Concrete	$12,846	$14,573	$17,117	$27,939	$379,357	$552,456	$552,456	$705,882
05	Structural Steel	$0	$0	$0	$0	$16,948	$30,364	$30,364	$37,366
06	Architectural	$0	$0	$0	$0	$697,177	$1,221,595	$1,221,595	$1,554,430
07	Piping	$0	$0	$0	$0	$287,273	$440,163	$440,163	$626,988
08	Electrical	$183,507	$237,834	$253,306	$237,599	$1,652,384	$2,415,424	$2,415,424	$2,722,956
10	Insulation	$0	$0	$0	$0	$110,985	$119,975	$119,975	$149,975
11	Coatings	$1,500	$1,500	$1,500	$1,500	$10,470	$18,465	$18,465	$23,085
14	Misc Directs	$60,552	$60,652	$60,652	$60,952	$267,491	$332,745	$332,745	$402,293
	Total Direct Cost	**$740,089**	**$1,145,395**	**$1,239,989**	**$1,779,904**	**$8,317,851**	**$13,633,623**	**$13,633,623**	**$16,703,440**
Construction Mgmt & Indirects		$143,200	$143,200	$143,200	$143,200	$1,417,400	$1,613,400	$1,613,400	$1,807,000
Engineering		$274,600	$274,600	$274,600	$274,600	$1,183,400	$1,354,200	$1,354,200	$1,498,200
Start-Up		$34,550	$34,550	$34,550	$34,550	$112,700	$170,660	$170,660	$212,075
Commercial - Insurance, Surety, Permits, Warranty		$57,400	$63,400	$64,600	$71,800	$191,700	$285,200	$285,200	$329,600
Escalation		$0	$0	$0	$0	$0	$0	$0	$0
Total Indirect Cost		**$509,750**	**$515,750**	**$516,950**	**$524,150**	**$2,905,200**	**$3,423,460**	**$3,423,460**	**$3,846,875**
Total Direct and Indirect Costs		**$1,249,839**	**$1,661,145**	**$1,756,939**	**$2,304,054**	**$11,223,051**	**$17,057,083**	**$17,057,083**	**$20,550,315**
Project Contingency		$62,492	$83,057	$87,847	$115,203	$561,153	$852,854	$852,854	$1,027,516
EPC Fee		$104,986	$139,536	$147,583	$193,541	$942,736	$1,432,795	$1,432,795	$1,726,226
Total Project Cost		**$1,417,317**	**$1,883,739**	**$1,992,369**	**$2,612,797**	**$12,726,940**	**$19,342,732**	**$19,342,732**	**$23,304,058**
Owner Cost - General, Taxes & Fees		$70,866	$94,187	$99,618	$130,640	$636,347	$967,137	$967,137	$1,165,203
Owner Cost - Owner Contingency		$74,409	$98,896	$104,599	$137,172	$668,164	$1,015,493	$1,015,493	$1,223,463
Total Project Cost Incl. Owner Cost		**$1,562,592**	**$2,076,822**	**$2,196,586**	**$2,880,609**	**$14,031,452**	**$21,325,362**	**$21,325,362**	**$25,692,723**

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