Hydropower Black Start

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Energy Efficiency and
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A Guidebook for Retrofitting Grid-Dependent Hydropower

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SUMMARY

Not all United States (US) hydropower plants were designed to provide black start, but they are increasingly needed to uphold resilience in the evolving electric grid. This guidance is designed to help understand the minimal retrofits required for grid dependent hydropower (GDH) plants behind the point of interconnection. For distribution connected hydropower plants or those with dedicated cranking paths, such upgrades can be sufficient for the plant to provide black start. For others, more coordination with the transmission system operator will be needed.

This guidebook answers a number of questions relevant to retrofitting hydropower plants with black start capabilities. For example, the guidebook answers:

- How flexible do the wicket gate controls need to be?
- Who needs to do hydro governor model validation, why, and how?
- How robust and flexible do the excitation and automatic voltage regulator controls need to be?
- What protection settings need to be adjusted?
- What relay(s) will need to be bypassed or overridden and at what risk?
- What is the electrical energy demand of the station load or auxiliary power systems?
- What should the strategy to energize transformer(s) along cranking path to address inrush currents be?
- How should the critical load restoration be sequenced?

In addition to outlining the specifications that hydropower plants need to meet for each component to be able to perform black start, this guidebook provides a set of case studies for specific upgrades needed at actual plants. Between the case studies of plants that have already performed black start retrofits and the examples of how this guidebook can be applied to scope future retrofits, five key themes have been identified for retrofit needs.

1. Protection needs "black start" mode: hydropower plants that are not designed with black start capabilities will have protections that prevent them from interconnecting to a "dead bus." These protections will need to be overridden in every retrofit case and a separate black start mode should be

established so that operators can safely switch between black start and grid connected modes, minimizing the risk to the plant.

2. Wicket gates need modern controls: digital governors accelerate the parameter tuning process and gate position sensors improve controllability, so plants with mechanical governors should be upgraded. Furthermore, a black start and islanding mode should be established for controls to maximize plant performance.

3. Robust excitation support: the DC system or excitation generator needs to be reliable enough to form and sustain the rotor electromagnetic field. These systems are typically undersized in plants that were not designed for black start, so they will need to be upgraded.

4. Turbine-governor model validation and operator training: validation of a standard hydro governor model is needed to characterize the dynamic response (i.e., inertial and primary frequency response) of the GDH. This is required for control development and old hydropower plants often have outdated or incorrect models. Operator training is also typically required to ensure the hardware retrofits are utilized correctly during the black start process.

5. Transformer and cranking path energization: any upgradation and control adjustment in front of the point of interconnection will depend upon the existing interconnection. Coordination with the transmission or distribution operator may be required.

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ACRONYMS

AC	Alternating current
AM	Anonymous case study hydropower owner
ARIES	Advanced Research on Integrated Energy Systems
AVR	Automatic voltage regulator
BO	Anonymous case study hydropower owner
BPA	Bonneville Power Administration
BR	Anonymous case study hydropower owner
DC	Direct Current
DE	Anonymous case study hydropower owner
DOE	Department of Energy
EMT	Electromagentic Transient
FRE	Fall River Electric cooperative
GDH	Grid dependent hydropower
GE	General Electric
HO	Anonymous case study hydropower owner
HPU	Hydraulic Power Unit
INL	Idaho National Laboratory
MVA	Megavoltamperes
MW	Megawatt
NERC	North American Electric Reliability Corporation
NGT	Neutral ground transformer
NI-CAD	Nickel-cadmium
NREL	National Renewable Energy Laboratory
PID	Proportional, integral, derivative
PSCAD	Power Systems Computer Aided Design
RMS	Root mean squared
SC	Synchronous condenser
SCR	Silicon-controlled rectifier
TOV	Transient over voltage
US	United States
USACE	United States Army Corps of Engineers
VAR	Volt-ampere reactive

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A Guidebook for Retrofitting Grid-Dependent Hydropower

1. INTRODUCTION

Small hydropower is well positioned as a solution to the need for black start services in rural and remote areas, driven by an increase in extreme weather and a shift toward variable renewable generation. On average, major power outages caused by weather have doubled in the last ten years [1]. This, paired with the rise of public safety power shutoffs for wildfire prevention during the same time frame have led to significant power outage costs to communities [2]. Since rural and remote communities are often weakly connected to the rest of the grid through a single point of transmission, they can be disproportionally impacted by these weather and wildfire related outages.

For those communities with small hydropower plants though, there is a potential solution. Retrofitting some of the 2,198 small hydropower plants with black start capabilities can help utilities and system operators provide power to critical services during emergencies. About half of these plants are located on the West Coast, where public safety power shutoffs are being practiced, and the rest can improve energy resilience during hurricanes or other weather events [3].

This report will guide utilities, hydropower owners, and system operators through a checklist of components that may need to be upgraded at small hydropower plants to enable black start services for their areas, and it will illustrate the process through case studies with real plant data. By focusing on the specifications for each component rather than specific models, the reader will be able to identify the minimum cost retrofit plan for a particular hydropower plant to enable black start and islanding of critical services. This process was demonstrated in the field at the Felt Hydropower Plant, where Fall River Electric Cooperative and Idaho National Laboratory were able to retrofit the grid dependent hydropower (GDH) plant to provide islanded power to critical services for $185,000 including hardware and labor [4]. The team has also shown that coupling small hydropower plants with ultracapacitors or batteries can improve the load carrying capacity, but batteries are not required to enable some level of black start and islanding [5]. More details on this case study can be found in Section 1.2.3 and the lessons learned from the demonstration have informed the rest of the sections of this report.

1.1. Grid Dependent vs. Black Start Registered Hydropower

A GDH plant is a hydropower plant that can only turn on and provide power when it is connected to a live bus. Different hydropower plants may have different reasons they are not able to start without a connection to the grid, but ultimately it is because they cannot complete one or more of the following steps:

1. A self-starting, on-site power source energizes controls, safety, communications, and excitation systems; restarts the cooling systems; and prepares fuel and fuel handling systems
2. Internal plant buses are configured for startup
3. The turbine is brought up to speed to generate power
4. All generators are powered to bring the plant into operation
5. The power from the plant energizes the plant transformers and nearby transmission or distribution lines
6. A cranking path is configured in the transmission or distribution lines to start up other generators or serve critical loads
7. Power is provided to generator startups or critical loads [6]

Not all hydropower plants with black start capability are or need to be registered as black start resources. Many large hydropower plants are currently registered with the North American Energy Reliability Corporation (NERC) as black start resources, but the requirements for registration are not worth the burden for some small hydropower plants that can still provide valuable services. In fact, 35-40% of all registered black start resources are hydropower plants [6]. Registering black start resources is part of the process of fulfilling the NERC requirement that all transmission operators create plans to restore power after blackouts. In order to get their plans approved by their reliability coordinators, transmission operators must register enough black start resources to execute the plan. Registering a resource requires proving that it can start without support from the bulk electricity system and energize a bus [7]. Completing these physical tests and any other studies required in the plan at least every three years is expensive, so it is more beneficial to register a few large plants that can start significant portions of the grid rather than many small plants. As such, even some small hydropower plants which have been previously tested for black start performance are not registered.

Because natural gas plants have traditionally been used heavily for black start, more black start resources will be needed as the grid transitions away from fossil fuels. It is likely that distribution connected resources will need to be used to supplement this service, and small hydropower plants are a big opportunity in this space [8]. Additionally, small utilities and co-ops, which only operate distribution systems, may not have the NERC black start requirements of a transmission operator but may want to improve their resilience postures in the face of public safety power shutoffs and other events that isolate them from the larger grid.

1.2. Existing Black Start Studies and Retrofits

While hydropower plants have traditionally been operated as base load, grid-connected assets, the largest were originally designed to provide black start and interest in retrofitting others with black start capabilities has increased in recent years. This section contains three examples of black start studies and retrofits that have already been completed to give an idea of what may be required for this type of project. Note that one of the themes across all three case studies is the need for a switch that the operator can use to flip between the normal protection scheme and a black start mode.

1.2.1. Black Start of Kingsley, and North Platte Hydropower Plant (1986)

A black start retrofit project at the Kingsley and North Platte hydropower plants is described in a 1990 paper from R. R. Lindstrom [9]. The North Platte facility, equipped with two 14.5 megavoltamperes (MVA) Francis turbines, and Kingsley, featuring a 52.6 MVA Kaplan turbine, underwent offline testing to fine-tune control settings. A switch was then installed to allow the operator to flip between grid-connected and isolated mode controls.

Some hardware retrofits were also required to enable black start at these plants. For example, a microprocessor was installed to automate the reset of turbine pitch control, obviating the need for a manual reset after large net-head variations. A microwave phone that did not depend on the alternating current (AC) electricity system was also installed to ensure communications could stay online during the black start process.

The generator interconnection process also required modifying the recloser relay to facilitate a hot generator/dead bus connection. Additionally, supervisory controls were assigned at the transmission substation to manage sync-check reclosing relays, allowing for dead bus/dead line breaker closure, which is crucial for cranking path energization.

Finally, the cranking path and startup procedures had to be modified to avoid sustained dynamic overvoltages. Energizing the generator step-up transformer and the 230/115kV transformers separately solved these issues, and the plant owners had to coordinate with the substation to ensure a reliable cranking path.

1.2.2. US Army Corps of Engineers (USACE): Cougar Dam Hydropower Plant (2020)

The USACE undertook a black start retrofit project in 2020. The project focused on the Cougar Dam hydropower plant, which has two 15 MVA, 6.9 kV Francis turbines [10]. The governor at the plant had no proportional, integral, derivative (PID) tuning, but the droop setting was set to 5%.

A significant part of this effort was overcoming the protections that prevent the generator from closing on a dead bus. For generator interconnection, the facility utilized line phase distance relays on the 115 kV line, which is owned by the Bonneville Power Administration (BPA). These relays must be energized with a voltage prior to current application, so they block interconnection to a dead bus. BPA provided written instructions to temporarily disable these relays for the test. While this temporary disablement posed a risk of non-tripping during a three-phase fault, a permanent solution was implemented by increasing the distance relay's zone 2 setting from 0.8Ω to 5.0Ω (hence increasing the physical distance of fault sensing location), which extended the zone 2 trip delay (so that it will not trip before zone 1) from 1.0 seconds to 2.2 seconds. Additionally, the generator breaker trip circuit was disabled to prevent the 6.9 kV breaker from tripping when the 115 kV line was open.

At the transmission substation, a temporary solution involved adding a jumper around the sync-check contact to disable it. For a more permanent fix, a sync-check bypass control switch will be installed, allowing operators to bypass the sync check only when necessary. The load pickup was limited to below 4 megawatts (MW), ensuring stable system performance during the initial stages of black start.

Personnel communication during the retrofit process was facilitated through satellite phones, ensuring uninterrupted coordination. This comprehensive retrofit strategy by USACE illustrates a practical approach to enhancing the black start capabilities of hydropower plants, ensuring they can effectively support grid restoration efforts.

1.2.3. Fall River Electric (FRE): Felt Hydropower Plant (2023)

In 2023, the Idaho National Laboratory (INL) collaborated with Mercury Governor and Fall River Electric Cooperative (FRE) to retrofit the Felt Hydropower Plant with black start capabilities. This project involved several key upgrades to the plant's control systems and equipment to enable it to start independently without relying on external power sources [4].

The plant started with bang-bang control of the wicket gates, which was a significant barrier to islanded operations and black start. To overcome this barrier, the plant was retrofit with a new control system, including programmable logic controllers for each unit, which enhanced the automation and precision of the plant's operations. The existing pilot valve was replaced with a proportional valve, and new sensors were installed to monitor gate positions and generator speeds, providing crucial data for the black start process.

To ensure the plant could initiate operations independently, the protection circuit, which contained multiple redundant safeguards against closing on a dead bus, had to be bypassed. Long term, the excited would need to be upgraded because the added stress on the exciter caused a contact to burn out following a line-ground fault at a rental transformer. The on-site batteries would also have to be upsized as they were found to be too small to power the auxiliary loads throughout the startup process.

Overall, retrofitting the Felt Hydropower Plant demonstrated the complexities, cost, and technical requirements of equipping old, small hydropower facilities with black start capabilities. One of the challenges of this project was the accelerated timeline, where retrofits and demonstration were performed over the course of two weeks with the plant only being taken offline for one week. For the cost component, installing the new sensors and controllers required cost $85,000 for parts, labor, and travel. Bypassing the protection relays cost $15,000 in labor, the power-hardware-in-the-loop simulations and site safety inspection cost $40,000, and control parameter modeling cost $45,000 for a project total of

$185,000. The project highlighted both the pathway to success and some areas requiring additional study, which this report addresses.

2. PERFORMANCE REQUIREMENTS FOR BLACK START

2.1. Wicket Gate or Nozzle Control Flexibility

During black start, the hydropower plant's active power output controls the frequency on the grid. In order to avoid damaging equipment, the plant will need to maintain the frequency close to its nominal value (60Hz in the US). The amount of power generated by a hydropower plant primarily depends upon the available head and water flow rate. Since the head cannot be directly controlled, this leaves the water flow rate as the primary control point for the plant's power output. The amount of water intake is controlled by the wicket gate (for reaction turbines) or nozzle opening (for impulse turbines), so these controls are critical for providing effective and safe black start services.

There are two primary control modes used in hydropower plants, which are best suited to different types of operation. In load control mode, a target power output is set, which can be adjusted to balance load changes. This can be achieved by setting a droop curve, which describes how the generator responds to deviations in generator speed by ramping power output up or down to balance system load. Once the system load is balanced, the generator will maintain its new load set point until another asset on the grid drives the system frequency back to its nominal value. For black start and islanded mode operation, however, the plant uses a reference speed target, since the hydropower unit is forming the grid. Therefore, the wicket gate or nozzle flow responds to load changes to drive the generator speed back to the reference value itself. This mode of control is referred to as "speed control" mode. Since the reference speed is set to synchronous speed, the droop is set to 0%, allowing power to fluctuate without the generator speed changing.

To enable speed control mode, the control system should at least have access to the speed of the turbine-rotor shaft and be aware of the instantaneous position of the wicket gate. Wicket gate position (for reaction turbines) or nozzle opening (for impulse turbines) is measured and fed back to the controller. Furthermore, PID-based wicket gate control needs to have its parameters tuned for islanded (i.e., speed control) mode operation. Theoretically, for a hydropower unit with water starting time T_w and mechanical starting time T_m, the PID settings should be the following [11]:

$$K_p = \frac{0.8 \times T_m}{T_w} \qquad K_i = \frac{0.24 \times T_m}{{T_w}^2}$$

$$K_d = 0.27 \times T_m$$

It should be noted that water starting time is the time to reach design flow rate throughout the length of penstock, from the moment water is released to the penstock at a given head. Furthermore, the mechanical starting time is derived as the twice of the inertia constant of the rotary mass.

It may happen that the wicket gate position change has been discretely actuated through a directional control valve for the GDH. To enable speed control mode of wicket gate control, such a valve needs to be replaced by proportional valve to enable continuous change in wicket gate position in speed control mode. The sizing of such proportional valve depends upon the capacity of the existing servomotor.

In summary, a hydropower plant's wicket gate or nozzle control system will be capable of performing black start if:

- The control system can access the generator shaft speed

- The control system can access the position of the wicket gate or nozzle opening
- The wicket gate position or nozzle opening can be controlled continuously to intermediate values
- A speed control mode has been developed with appropriate PID parameters.

2.2. Excitation and Advanced Voltage Regulator Control Flexibility

Excitation control is the broader system that manages the magnetic field strength of the generator through the excitation current influencing both the reactive power and terminal voltage. The automatic voltage regulator (AVR) takes voltage signal input from the stator and creates a control signal to automatically maintain the generator's terminal voltage at a stable set point based on the voltage droop or direct voltage control mode of operation. Depending on design, AVRs in black start applications can rely on either external power source (such as a battery system) to provide excitation or use mechanical power of rotating turbine to produce excitation (rotating exciters).

2.2.1. Overview of Excitation Systems

Hydropower plants can provide black start more quickly and reliably than inverter-based resources, but this process puts certain requirements on the excitation system. During black start, hydropower plants and other synchronous generators can use a hard start method for energizing the network at the voltage levels close to nominal since they can provide required levels of inrush currents when energizing transformers, transmission lines, electric motors, etc. In contrast, inverter-based generators do not have overcurrent capability and need a soft-start method for black start by gradually increasing the voltage from 0 to nominal level.

To control the reactive power and therefore system voltage during normal operation and black start, synchronous generators have excitation systems that supply and regulate the level of direct current (DC) field current. The excitation system of a generator is specified to meet the power requirements, dynamic and transient response characteristics of the power system it is connected to. Modern excitation systems of synchronous generators used in power plants can be divided into two main groups: (1) brushless rotating excitation systems; (2) static excitation systems.

Brushless exciter systems use shaft-mount permanent magnet alternator and rectifier with direct connection to generator field winding. This configuration eliminates the need for brushes and slip rings and is normally used in smaller generators with power capacity up to 10 megavoltamperes (MVA) or so. Permanent magnet alternator also eliminates a need in field flashing capability for startup. Also, permanent magnet alternators can increase excitation current without any impact from the load of the generator, provide higher levels of fault current and maintain that current for longer period. However, a permanent magnet alternator-based brushless excitation system will add some length to a generator shaft system and can potentially reduce the statistical reliability of the generator because of additional rotating parts that can fail. General diagram of brushless permanent magnet alternator-based excitation system is shown in Figure 1.

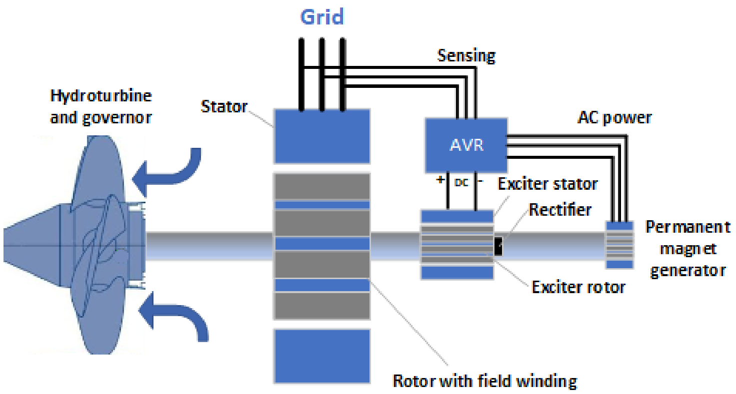

Figure 1. General diagram of brushless excitation system (Source: NREL).

Static exaction systems are most commonly used in larger hydro-generators. Static exciters need brushes and slip rings, and use either autonomous DC supply, or station supply for field flashing. Static excitation systems are based on power electronics and can be either full-inverting or semi-inverting bridge types. The choice of bridge configuration depends on the need to reverse DC voltage to force faster field suppression and reduce generator terminal overvoltage under load rejection conditions. In general, static exciters have faster response than brushless rotating exciters. Under black start conditions, field flashing capability may be needed for static exciters. General diagram of static excitation system is shown in Figure 2.

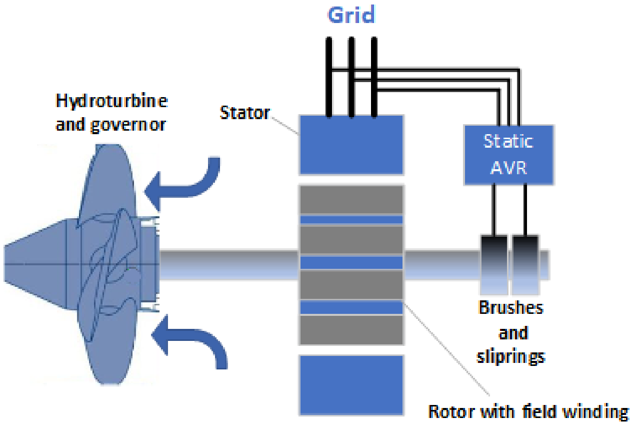

Figure 2. General diagram of static excitation system (Source: NREL).

Depending on the type of excitation system, some additional equipment may be needed to ensure robust black start capability. In case of static exciters, an external power source (battery, diesel genset, etc.) is needed to start and check the status of the exciter, even before the generator starts spinning.

2.2.2. Impact of Excitation System on Generator Dynamic and Transient Performance

To demonstrate the impact of different types of exciters on black start performance and low voltage ride-through, which is important for islanded operation, the NREL team simulated scenarios with a Power Systems Computer Aided Design (PSCAD) model. Both static and rotating governor models were used in simulations to identify differences in system response to various conditions. The conceptual diagram of PSCAD model used for simulations under dynamic and transient conditions is shown in Figure 3.

This system consists of a 25 MW hydro power plant connected to the load bank via overhead medium voltage transmission line. The model also includes a hydro turbine and governor models. The hydro turbine was modeled as a turbine with non-elastic low-head water column without a surge tank. A governor model with PID controls including pilot and servo dynamics was used. The turbine and governor models are set to operate at direct speed control to maintain constant frequency during black start.

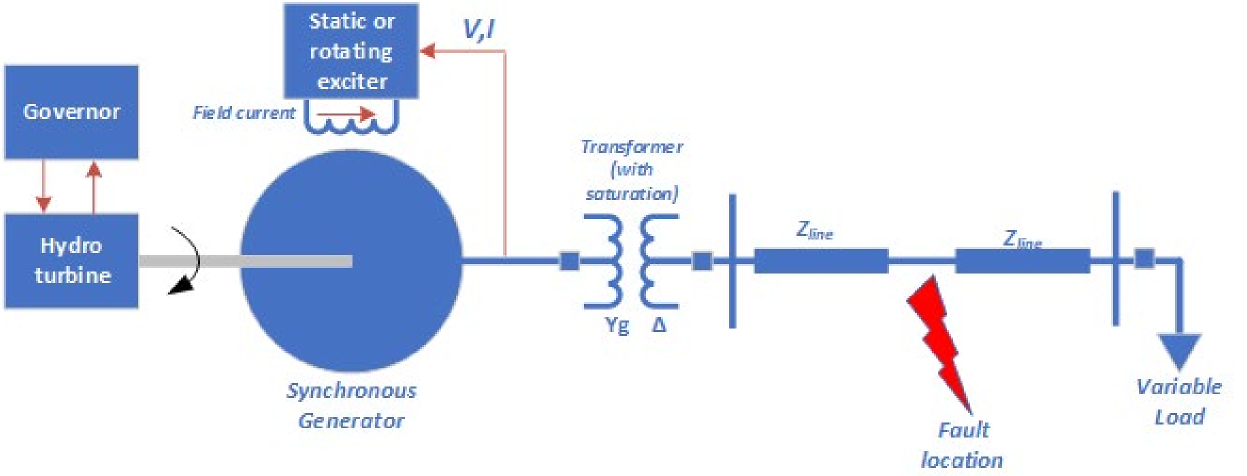

Figure 3. Diagram of PSCAD model for exciter simulations (Source: NREL).

Figure 4 shows system response during black start simulations with a smaller 10% load steps using either static or rotating exciter systems. At t=10 s, the generator contactor closes allowing energization of generator transformer and transmission lines (no load connected at this point). The combined active load of transformer and transmission lines is very small (only resistive losses in the system), so this loading impact on generator speed is negligible. At t=18s, consecutive 10% load steps are initiated (load reactive power level is kept constant).

During initial active power steps, the power factor is low, and some low frequency reactive power and voltage oscillations can be observed for a case with rotating exciter. If a static exciter is used, the system exhibits stable behavior at any power level while the rotating exciter exhibits some damped oscillations. Generator speed deviations are deeper for each load step as power levels increase (lower graph in Figure 4). However, static excitation system provides better frequency response because of better stability and faster response time.

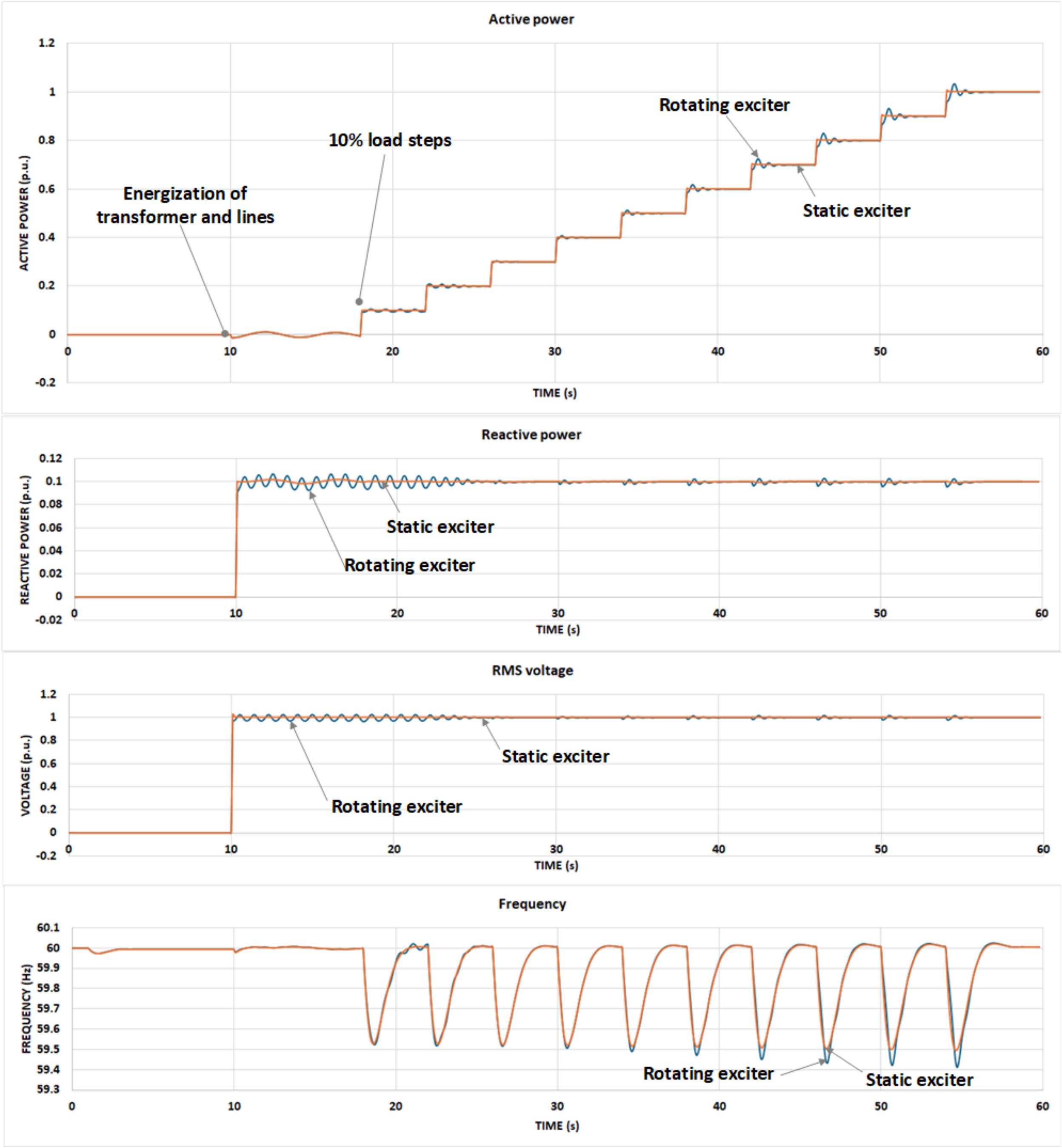

Figure 4. Generator response to 10% load steps (Source: NREL).

As shown in Figure 5, system response during fault conditions is very similar between the two types of exciters with only some short-term oscillatory behavior in the case of a rotating exciter that are quickly damped. The turbine and generator are essentially unloaded during this voltage fault, causing some acceleration. The transient behavior of the system can be further improved if integrated battery energy storage is used.

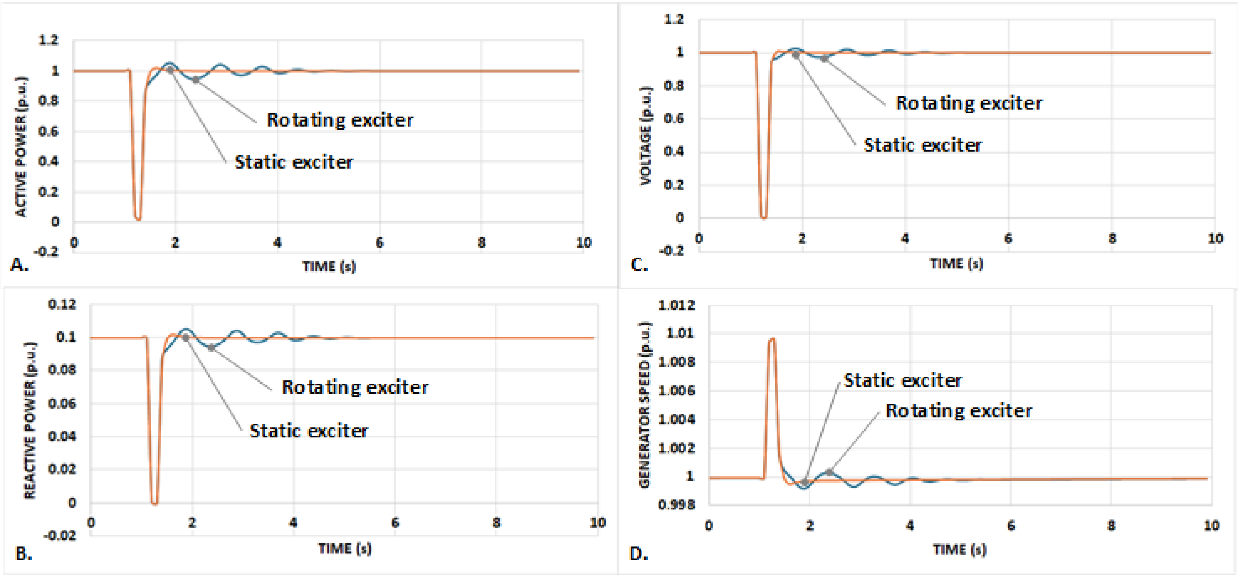

Figure 5. Generator low voltage ride-through response comparison for rotating and static exciters (200-ms 3-phase ground fault) (Source: NREL).

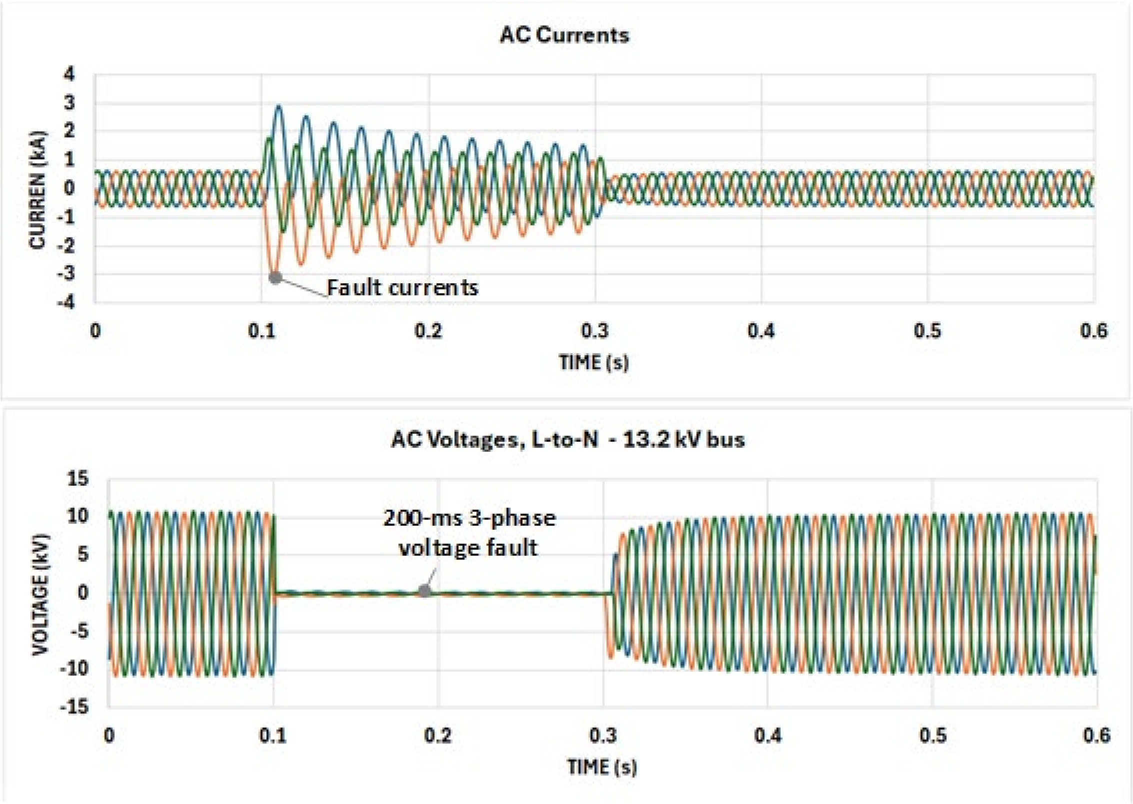

Figure 6. Fault currents (Source: NREL).

2.2.3. Conclusions

The main impact of excitation system is on the resiliency and design of hydro power plant itself (exciter investment cost, need in exciter backup power for black start, exciter maintenance cost, etc.).

Based on conducted simulations, the impact of exciter system on plant response is important but adequate performance can be achieved with different types of exciters if they are appropriately tuned. Some parameters of the exciter and AVR system may need to be set specifically for black start mode. For example, if the hydro generator is normally set to operate in voltage droop mode, then the operator may consider switching to direct voltage control mode during black start and islanded operation. Voltage control gain and time constants may be re-tuned as well to provide faster system response during load steps.

Correct settings for AVR parameters for the plants that are not designed for black start can be obtained through power flow and electromagnetic transient (EMT) simulations for each specific case. These excitation system parameters depend on the parameters of the generator and transformer, the electrical characteristics of the point of interconnection, the grid services that generator is expected to provide, and the parameters of loads (and magnitude of load steps) that the generator needs to support during black start and islanded operation. The important parameters to consider when designing excitation control for a hydro generator include both steady-state and transient requirements:

- Exciter rated voltage and current, field rated voltage and current
- Ceiling voltage under no-load, loaded, and disturbance conditions
- Excitation system time
- Under and over excitation limiters, Volt/Hz limiter
- Volt-ampere reactive (VAR) and power factor control systems
- Power system stabilizer in grid-connected mode
- Pole slipping protection.

These parameters need to be set after conducting power flow and EMT simulations for each hydro power plant. Their excitation system parameters depend on parameters of the generator parameters, parameters of the transformer, electrical characteristics of the point of interconnection, grid services that generator is expected to provide, and parameters of loads (and magnitude of load steps) that generator needs to support during black start and islanded operation.

2.3. Protection Relays

The use of protection relays in electrical power systems is crucial to mitigate the impacts of abnormal operations. Protection relays use signals such as current and voltage to monitor electrical events and protect equipment (e.g., generators and transformers) and operators against damage when abnormal and unsafe conditions occur.

From the data collected during this study, it has been observed that GDHs can be safely operated if some basic protections are missing. This is because the external grid has large inertia and is tightly regulated, providing frequency and voltage support and ride-through capabilities, thus preventing small hydropower plants from being directly exposed to abnormal grid conditions. This is, however, not the case when hydropower plants black start in isolation and support stand-alone operations. Due to the absence of the external grid, standalone grids have significantly reduced inertia. This causes standalone operations to be more prone to instabilities and are more likely to experience abnormal conditions such as over/under frequency, current, and voltage. Thus, for black start and standalone operations, the protection of the hydropower plants must sufficiently arrest any abnormal conditions that may occur. To guarantee protection during black start and standalone operation, the hydropower plants (and other equipment used) should at the minimum be protected against:

1. Overcurrent currents
2. Negative sequence current and unbalanced loading and faults

3. Under and over voltage
4. Under and over frequency
5. Loss of excitation
6. Overexcitation
7. Desynchronization
8. Reversal power flow
9. Overload.

The set of relays that offer this minimum protection are identified below (Table 1). While these relays (Table 1) are often already installed in GDHs, some must be reconfigured to support black start. These include the 25 sync-check relay, 81 O-U over/under frequency relay, and 27/59 over/under voltage relay. Contrary to GDHs where the 25 sync-check relay is configured to only allow generator breakers to close on a live bus, for black start the relay must be reconfigured to allow the breaker to close on a dead bus since the external grid is absent. Due to large power swings, the 81 O-U over/under frequency and 27/59 over/under voltage relays must be reconfigured for wider frequency and voltage thresholds to prevent nuisance tripping of generators, as opposed to GDHs where narrower thresholds are used since the external grid provides tighter regulations. These recommendations, among others, are provided below (Table 1), together with why the protection relay should be used, and what equipment it should protect. Being the minimum protection, these relays can also be used with other relays already present in the system if their configuration supports black start.

Table 1. Minimum protection relays required, functions, and recommendations during black start.

Relays	Function	Recommendation during black start
25 Sync-check relay [12]	Permits breaker closure when the desired maximum phase angle conditions have been held for a specified minimum of time. The relay measures the phase angle between single-phase voltages of the line and the bus. Then sync-check verifies that this angle is less than the PHASE ANGLE selected on the front panel. If the measured angle meets the set criteria for the TIME DELAY specified in front of the panel, then the SYNC output contact closes.	This relay decides whether the generator breaker can close on a live (hot) or dead bus. Since there is no external grid during black start, the 25 sync-check relay of the generator that starts the grid must be configured to allow the generator breaker to close on a dead bus (failure to implement this will require manually bypassing the relay, which can compromise the protection of the system). Thereafter, the 25 sync-check relays used by the other generators (if any) can be configured to allow breaker closure on a live bus. Installing this relay for each generator ensures synchronized operation when multiple generators are paralleled for co-generation. In the case of the generator used to start the grid: • If its 25 sync-check relay has condition switches (such as in the BE1-25 relay), then the condition switch for Live Line/Dead Bus can be toggled ON to allow the generator breaker to close on a dead bus. This is assuming that the generator is on the Live Line-side and the standalone grid to be powered is on the Dead Bus-side. • If the sync-check relay setup does not have condition switches, then it is recommended

Relays	Function	Recommendation during black start
		that another sync-check relay dedicated to black start should be installed and solely configured to allow connection to a dead bus. Then manual or automated sensing can be used to switch between grid-connected and black start operations. Despite the redundancy, this arrangement provides flexibility to perform black start when the need arises.
81 O-U Main bus over/under frequency [13]	Monitors a phase frequency and protects generators against under/over frequency.	Due to the possibility of large power swings during black start, less strict frequency thresholds should be used to prevent nuisance tripping of the generator, e.g., 57 – 63 Hz. Generally, the frequency thresholds being selected should be within the acceptable range of the generator and the frequency thresholds used should be such that prevent the nuisance tripping of the generators during black start.
27/59 Under/over line voltage relay [14]	Protects generators and transformers against under/over voltage.	Due to the likelihood of large power swings during black start, this relay should be used to protect generators and transformers against under/over voltage. Also, less strict voltage thresholds can be used to prevent nuisance tripping.
51V voltage restraint overcurrent [15]	Provides a phase short circuit protection to generators and applications where voltage restraint is an advantage.	Should be used to protect generators considering their ability to: • Provide improved sensitivity to overcurrent relaying, a capability it achieves by making the set overcurrent operating value proportional to the applied input voltage. • Provides better coordination and fault detection than plain overcurrent relays, especially in the case where the fault current may vary and drop below the normal rated line-current under different fault current source conditions.
50/51 Overcurrent relay [16]	This is a nondirectional phase or ground relay that monitors the magnitude of a single-phase ac current and provides accurate instantaneous and time overcurrent protection.	Should be used to protect distribution transformers and generators against overcurrent.
46 Generator phase balance or negative sequence overcurrent relay [17]	Protects generators against negative sequence current and unbalanced loading and faults.	High likelihood of unbalanced loading in isolated grids demands using this relay to protect generators against negative sequence current. Set current monitoring threshold to the allowable negative current of the generators.
32 Directional power relay [18]	Protects from reverse power flow. Also checks the minimum forward power flow setpoint against the plant's power need.	• Should be used to protect generators against reversal power flow, overload, and motoring. • Should be installed for each generator when there is paralleling of generators to co-generate.

Relays	Function	Recommendation during black start
		• Set the minimum forward power flow setting to that of the plant's power need. • Time delays should be used to prevent nuisance tripping caused by transient power flow (surges) that may result from synchronizing or system disturbances. • The relay must be sensitive enough to detect power levels lower than those required to motor the generators. Sensitivity is much required for hydro turbines. The motoring threshold should be set to 0.2 – 2.0 percent of the plant's rated power. • Power factor must be greater than 0.10 as this is the range where the relay is effective.
Stator ground fault overvoltage relay: 64S, 64G1, 64G2 and 59N, 59D, 27TN [19] [20] [21] [22] [23]	Provides stator ground protection for generators.	• To protect against stator ground fault, ensure that the generator neutral is grounded through the neutral ground transformer (NGT) • Connect 64S, 64G1, or 64G2 on the primary side of NGT while 59N and 27TN on the secondary side of NGT. • 64S, 64G1, or 64G2 can monitor fundamental frequency and third harmonic voltage present during normal operation. 59N can only monitor the fundamental frequency and so 27TN can be used as undervoltage element tuned to detect third harmonics. • The 64G1, 64G2, and 59N have blind zones where they provide 90-95 % protection of the stator winding; thus, 64G1 and 64G2 have 5-10 % sensitivity (i.e., can start detection when the fault has covered at least 5 % of the winding). By contrast, 64S provides 100 % protection, hence protects the whole stator winding. Therefore: • On the primary side of NGT, 64S should be used considering its ability to provide a 100 % protection of the stator winding (most recommended protection). • On the secondary side of NGT, 59N and 27TN should be used. 59N provides 95 % protection while the additional 5 % protection near the neutral can be provided by 27TN or 59D. • The 64S relay must be deployed with (these features are already included in some of the off-the-shelve 64S relays): - a 20 Hz injection source, - a bandpass filter with center frequency of 20 Hz, and

Relays	Function	Recommendation during black start
		- a 20 Hz measuring current transformer.
64 Field ground fault relay [24]	Detects and annunciates ground faults in normally ungrounded circuits such as the field winding of a synchronous generator. These ground faults must be removed quickly since a second fault would result in serious damage to the field winding.	Should be used to protect generator field windings. To ensure that the field winding is protected, the rotor iron must be grounded. The grounding path through the rotor winding is not reliable for arresting ground faults in field windings. Recommendations on rotor grounding should be obtained from the machine manufacturer.
87G Generator differential relay [25]	Protects transformers against overcurrent. 87G relays are single- or three-phase devices designed to provide selective, high-speed, differential relays that protect generators against overcurrent.	The relay should be used to protect generators against fault current considering its ability to detect mismatches between the current flowing in and out of the generator circuit. This relay is suitable for generators with any terminal voltage value and rating of at least 1 MVA.
87T Transformer differential relay [26]	Protects transformers against overcurrent.	• Should be used to protect transformers against overcurrent since it ensures that currents flowing in and out of the transformer circuit are closely matched. • Inrush current is highly likely to happen during black start. Hence, the relay should be used to provide transformers with ride-through capabilities during inrush current and external overvoltage caused by magnetization. It uses the second harmonic to provide ride-through capability during magnetizing inrush current, and the fifth harmonic to inhibit relay operation during overexcitation, which prevents nuisance tripping.
40 Generator loss of excitation field [27]	Provides protection by monitoring the field excitation (measuring the magnitude and direction of var flow) and tripping before serious damage is done.	• Should be used to monitor generator excitation fields to detect any loss of excitation. Normal operation requires that the generator terminal voltage lags that of the bus. This relay ensures that the generator supplies and not drawing reactive power from the grid. • A time delay can be set to prevent mis-operation for transient conditions such as power swings due to synchronization or external fault clearing.
24 Overexcitation relay [28] [29] [30]	Used to detect unacceptably high induction in generators and transformers. High induction can occur in a transformer if the generator being connected to starts up or got disconnected from a full load operation and the voltage regulator fails to act fast, or at all, thereby leading to voltage increase.	The relay should be used to protect against the saturation of the iron core, which can cause large hysteresis and eddy current losses.

Relays	Function	Recommendation during black start
	Load shedding can also cause excessive voltage which can result in the overexcitation of the transformers connected to the system.	
60 Generator voltage balance relay [31] [32]	Provides a high-speed response to block other devices from improper tripping or malfunctioning because of blown fuse in a potential transformer circuit.	Should be used in conjunction with overcurrent relays (voltage-controlled or voltage-restrained types), impedance-measuring relays, synchronizing relays, voltage regulators, and static systems.
50BF Breaker failure relay [33]	Protects power system against faulty breakers, (i.e., when the monitored breaker fails to trip. It detects this fault and activates to initiate backup procedures).	• Should be used with the main breakers of generator and transformer to prevent continuous flow of current into their faulty circuits sometime after a circuit breaker has been instructed to interrupt the circuits. • The backup procedure initiated by the relay must be designed to isolate both the failed breaker and the faulty circuits associated with the generators and transformers.
78 Out-of-Step protective relay	Operates at a predetermined phase angle between either two voltages, two currents, or between a voltage and a current. It detects out-of-step conditions by monitoring the rate of impedance change at the generator terminals.	Should be used to protect generators in the incident of out-of-step which occurs when the disturbances between connected generators cause loss of synchronization between parallel generators or different areas of the power system. The relay disconnects any generator that loses synchronization to prevent the total collapse of the grid and damage of the affected generator.

In summary, the protection of standalone hydropower plants is properly set up if:

- The existing plant protections have been accurately cataloged
- All missing protections from Table 1 have been installed to protect the hydropower plant and transformers
- There is a 25 sync-check relay that has been dedicated for black start so that the one used for grid-connected operation is not overridden or reconfigured for each black start, reducing the risk of human error and compromising system protection
- Less restrictive frequency and voltage threshold settings have been used in the 81 O-U over/under frequency and 27/59 over/under voltage relays to avoid nuisance tripping during power swings

2.4. Auxiliary Systems

Hydropower plants need the auxiliary system to function, whether in grid-connected or standalone operations. These auxiliaries typically consume less power than those of nuclear and steam – about 0.5 – 1.0 percent of the total power generated by the plant. Being a critical part of hydropower plants, hydro operators must ensure that the auxiliaries used during black and standalone operations are reliable. Auxiliaries in hydro stations can include:

- Valve controls such as gate, penstock, reservoir, and turbine controls

- Hydraulic power unit (HPU). HPU is analogous to a power amplifier that actuates wicket gate position or nozzle opening changes based on the control command.
- Electric drive for valve motors
- Hydropower excitation system
- Governor oil pump motor
- High pressure oil pumps
- Bearing forced lubrication pumps
- Unwatering and drainage pumps
- Computer control station
- Microprocessor-based controls
- Lighting
- Ventilation fan
- Power outlet circuit
- Switchgear power circuit.

Similarly to diesel generators, batteries can be used to power auxiliaries and are increasingly adopted in hydro stations. This is driven by batteries' size, dependability, and performance. Two battery systems are adopted in hydro stations. These are the flooded liquid electrolytes batteries and sealed maintenance free batteries. As discussed below (Table 2), various battery types can be grouped under these battery systems. These batteries can be used to power auxiliaries when black starting hydropower plants. Also, the operator must ensure that the batteries are long-lasting and in good condition.

Table 2. Commonly used batteries in hydropower plants [34].

Types	Normal expected life[a]	Approximate number of full discharges	Approximate hour capacity range in small hydropower plants	Relative cost	Advantages	Disadvantages	Remarks
Flooded Liquid Electrolytes							
Lead Acid Flat Pasted Cells	Base (10 – 12 years)	1000 - 1200	6 – 4000	Base	Provides significant number of full discharges over life	Requires more watering, emits more hydrogen, needs monthly equalizing charge, and requires separate well-ventilated room	Suitable for small hydropower plants below 5 MW, requires separate ventilation room
Lead Acid Tubular	1.1 x base	50 - 100	6 – 4000	1.1 x base	Requires less watering, emits less hydrogen, higher power density for their size, high current capacity, does not require monthly equalizing charge		Suitable for high current discharge, suitable for medium to long duration with small current discharge, and recommended for attended hydro stations
Lead Acid Plante	1.8 x base	1000 - 1200	6 – 4000	1.4 x base	High energy density, durable, can function at room temperature higher than 25℃		Suitable for large current demand over short periods and generally

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a. Lifetime estimates strongly depends on cell/plate construction, duty cycle and quality.

							used in hydro stations
Nickel Cadmium Alkaline (NI-CAD)	3 x base	1200	2.5 – 1000	3 x base	Low maintenance, longer life, low self-discharge, performs well in low temperature and not damaged by freezing temperatures, does not deteriorate in discharge conditions, does not release corrosive fumes	Higher cost and at 1.2 V per cell, required higher number of cells to attain a rating of DC battery, insufficient historic operation experience	Suitable for small hydropower plants at high altitude and small unattended hydro stations
Sealed Maintenance Free Batteries							
Lead Acid/Special Alloy Sealed Maintenance Free Batteries	1.4 x base	300	200 – 400	1.4 x base	Water addition is not required, does no emit hydrogen	Cell plates or electrolyte level is not visible, and cells are in opaque plastic containers, insufficient historic experience in power houses	Suitable for hydro stations less than 5 MW and where separate room is not available

In summary, batteries can be sized for black start and standalone operations as follows:

- Determine the total rating of the auxiliaries and duration of battery support
- Choose the desired initial and final state of charge of the battery

Then, the battery capacity can be calculated as:

$$C_{bat} = \frac{P_D \times t}{SOC_0 - SOC_1}$$

where:

C_{bat} = battery capacity (calculated in kWh or MWh)

$P_D =$ auxiliary system rating (in kW or MW)

$t =$ period auxiliary unit is supported by battery (in hours)

SOC_0 = desired initial state of charge of battery (in percentage)

SOC_1 = desired final state of charge of battery (in percentage)

Note that:

- P_D can also consider demand aside from that of the auxiliary system if the operator desires the battery to also participate in providing frequency support during standalone operations. In this case, the operator may consider the peak (maximum) and baseload (steady) demands and duration for which the battery is required to provide support.
- t can simply be the duration that the operator would like the battery to last considering the initial and final state of charge
- Computing C_{bat} also allows to determine the capacity upgrade that an existing battery needs considering load demand, duration, and state of charge.

2.5. Transformer Energization

Transformers are one of the essential components of power systems considering the capability that they provide in stepping down/up AC voltages. Transformer energization is a regular operation in isolated grids, distribution systems, and transmission networks, and associated operational challenges are well known [35].

Increasing grid resilience may require that the generator transformer is switched on for generation to balance demand, switched off to protect generator or reduce generation surplus, and switched on/off to configure the grid's cranking path for isolated operation. The latter is the case when small hydropower plants are used to power standalone grids. This involves black starting the isolated grid and switching on/off the generator and point of connection (or distribution) transformers. Hence, transformer energization and re-energization should be expected when black starting hydropower plants for standalone operation.

However, energizing transformers results in the device drawing relatively large amounts of initial inrush current which decays overtime to a much smaller steady state magnetizing current. The transient magnetizing current that occurs during magnetization is caused by the saturation of the transformer iron core, where a small increase in voltage results in large current being drawn by the transformer. This can impact the transformer itself and the network in that there can be voltage drop across the network impedance, and a drop in the line voltages which gets worse toward the point where the transformer is connected. This can be characterized by the root mean squared (RMS) voltage drop, and the transient overvoltage (TOV) due to the resonance of the inrush current harmonic components and the resonances of the system. The inrush current is exemplified below (Figure 7), which shows that as the transformer core saturates, a small increase in voltage leads to a large inrush current. A TOV lasting a few seconds can damage surge arresters connected between phase and ground to protect transformers from switching and lightning surges, which can in turn make transformers vulnerable.

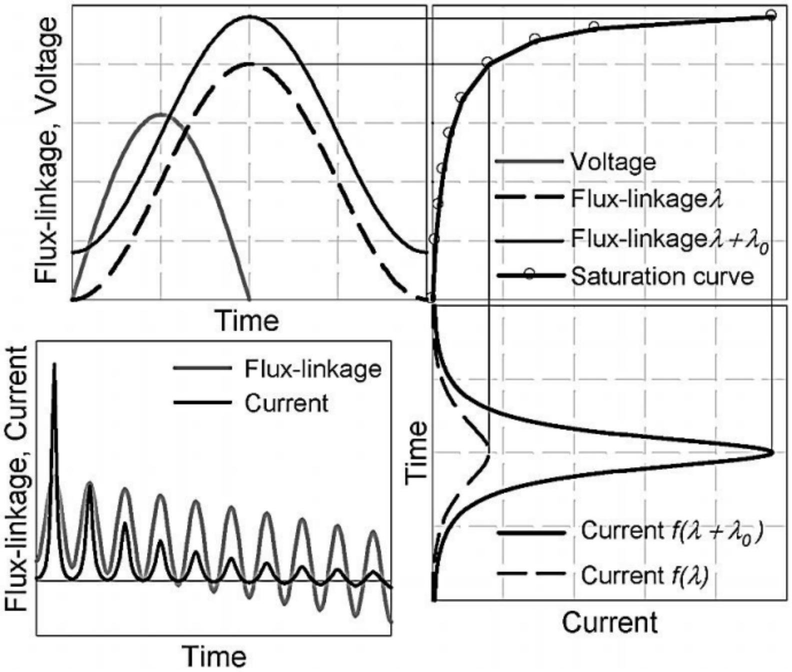

Figure 7. Qualitative and simplified representation of the inrush current and the impact of residual flux [35].

Inrush current is dependent on two random parameters which are the residual flux in the core before energization and the circuit-breaker point-on-wave closing times. Their dependency on uncertain parameters causes current and voltage variations to be indeterministic. A general rule, however, is to ensure that the currents and voltages do not exceed certain magnitudes (e.g., an RMS-voltage drop limit or the equipment overvoltage tolerance level).

There could also be the case of pseudo-inrush which occurs during recovery after a voltage sag event, such as after a fault is cleared. Also referred to as re-energization, this is an event that occurs when a transformer in operation is driven into saturation after a fault is cleared and the normal system voltage is restored at the terminals of the transformer.

Since power networks tend to have low resonant frequencies and higher impedance during black start, the magnitude of inrush current needs to be mitigated to reduce RMS-voltage drop and TOV. Two methods can be used to "soft start" transformers during black start. These are:

1. Point-of-wave closing: This involves controlling the closing times of the energizing circuit breaker. This helps to eliminate the transients, i.e., the inrush current, the RMS-voltage drop and TOV. This method is considered the most effective technique for limiting inrush current and its consequences.
2. Reducing voltage level: This involves reducing system voltage via e.g., adjusting the on-load tap prior to energizing the transformer. This also has proven effective in reducing inrush current and its consequences.

Any of these methods can be used to soft-start transformers during black start. This has the benefit of preventing wrong relay tripping, since large inrush current can be misinterpreted as fault current.

In summary, a hydropower plant is ready to energize transformers during black start if:

- The cranking path has been determined
- The inrush current has been determined either analytically or by simulation. Inrush current can be estimated using

$$I_p = \frac{\sqrt{2}V_m}{R}$$

where

I_p = the transformer inrush current

V_m = the plant maximum voltage

R = the DC resistance of the transformer

- A soft-start mechanism is in place to reduce inrush current to acceptable levels
- If a soft-start mechanism is not installed, then ensure that the inrush current magnitude does not exceed the tripping threshold of current protection relays for plant and transformer.

2.6. Dynamic Models for Transient Stability Simulations

Besides upgrading components to enable black start, it is important to assess the cranking path (the portion of the grid that needs to be energized before serving the critical loads), its existing ownership, its operation and its control [36]. Cranking an islanded grid, not owned and operated by the same entity as the hydropower plant will be more logistically challenging. The hydropower operator will need to coordinate with grid operator to plan “black start” mode setpoints to allow dead bus interconnection, line and transformer energization.

While it is important to plan how the grid will be reconfigured for black start, it is even more important to consider how the hydro units will respond during black start and standalone operation. Since black start is done when the hydropower plants are offline, it should not be assumed that the plants would respond similarly to when grid connected. Having a prior knowledge of how the plants (and connected components) would respond is crucial as this helps to derisk the operation. Attempting to gain insight by physical testing, numerous field measurements, and trial-and-error methods can be costly, unsafe, inefficient, and restrictive. This is why using dynamical models is important as simulating those allows us to gain insight on how the plants would respond under black starting and isolated conditions.

Simulating dynamical models mimicking hydropower plants (and connected systems) allows to reduce physical testing and trial-and-error efforts, simulate large range of scenarios that may arise during black start, assess system performance under different black starting and islanded conditions, perform stability analysis that allows to determine controller settings that support plants’ operation, perform short and open circuit analysis, verify system initializations that are stable, study the impact of transformer inrush current and faults, and investigate the impact of incorporating battery storage.

Note that results obtained from dynamical simulations are only as good as the quality of the dynamical models used. To obtain results with practical relevance, hydropower plants (and connected systems) must be accurately modeled. This starts by accurately modeling the hydro governor and turbine; calculating the plants’ aggregate inertia and any damping factor that may be present; measuring the water time constant, flow rate, and various heads that may be present during black start; modeling synchronous generators and excitation controls, transformers, and power lines; modeling the loads and determining the steps in which loads should be restored during black start; and modeling energy/battery storage systems that may be incorporated for black start.

Transient stability simulations can be performed using power systems simulation software. Real-time validations can be carried out using real-time digital simulators and the testing can be software-in-the-loop and hardware-in-the-loop. Simulations and hardware-in-the-loop testing, and stability studies were carried out before the onsite black starting effort of Felt Power Plant (Section 1.2.3). This allows us to investigate stable operating points, stable hydro governor settings, plant's response to practical water heads and water time constants, appropriate loading steps, transformer response, battery storage impact on plant's response, and stable storage settings. This allows us to gain insight on the system response under different scenarios, derisk plant's operations, and ensure stable black start.

The development of a new or revision of an existing dynamic model for the transient stability simulation, can start with reference to NERC Reliability Standards: MOD-027-1 for wicket gate or nozzle opening control, MOD-026-1 for excitation control and MOD-033-1 for cranking path models. These standards apply to black start registered hydropower plants, but they can also be used as references for model development of non-registered black start capable plants. As such, the degree of adherence to such standards for model validation can vary based on plant operators' reliability goals, jurisdiction over cranking paths, and control complexities. Furthermore, auxiliary load (especially motors) and cranking path transformers characteristics should be captured within the dynamic model to account for starting and inrush currents respectively. This will help to accurately identify acceptable range of load steps during restoration and any modification needs of the existing ride-through settings of the protection and relay settings all the way from black starting hydropower unit, via the cranking path, and to the critical loads.

In summary, a hydropower plant black start demonstration has been sufficiently derisked through simulation if:

- Plant parameters like inertia, damping factor, water time constant, flow rate, and typical head range have been measured
- Accurate governor models have been developed
- Accurate excitation control models have been developed
- Accurate cranking path models have been developed
- Other generation assets or energy storage assets used to support the black start have been modeled
- If the plant will be registered with NERC as a black start asset: compliance with MOD-27-1, MOD-026-1, and MOD-033-1 is confirmed
- Simulations have shown that the plant can maintain stable operations during black start and islanding across a range of possible conditions.

3. CASE STUDIES FOR APPLYING RETROFIT GUIDANCE

This section conducts a study applying various discussions above to utility-run small hydropower plants with the aim to determine whether these plants can black start and to recommend changes (modifications, retrofits, and upgrades) that need to be made for the plants to black start.

To conduct this study, a public call was made requesting for the participation of small hydropower plant owners (of size less than 10 MW) whose plants have at no point been black started. The call indicated that all interested partners will participate in the study at no cost, except for the data that will be requested of them for the study. The call was announced on the National Hydropower Association Newsletter, the INL News Release, the Homeland Security News Wire, and the Low Impact Hydropower Institute. Five utility companies showed interest within the timeframe of call. At a request to conceal identity, these utilities have been labeled as follows:

- AM: operates small hydro units with total output of 4.8 MW
- BR: is a customer-owned, non-profit municipal utility that operates a 5 MW hydropower plant
- HO: operates a 0.5 MW hydropower plant.
- BO: operates small hydro units with total output of 7 MW
- DE: operates a 5.117 MW hydropower plant.

The plants involved are being operated in grid-connected mode and have not been used offline to black start and support standalone operation. The data requested from the utilities are as follows:

1. Mode of operation (run-of-river, etc.)
2. Turbine installed capacity
3. Turbine type (Kaplan, Francis, etc.)
4. Synchronous generator installed capacity
5. Manual of the synchronous generators used at the plant.
6. Operating head
7. Water time constant
8. Hydro governor model
9. Type of governor control valve (open-close, or PID[b] controlled)
10. Type of hydro governor (digital or analog)
11. Hydro governor settings (i.e., PID settings)
12. Type of excitation and control
13. Guide vane sensors (present or absent)
14. Generator damping coefficient
15. Plant aggregate inertia (i.e., inertia of generator + turbine + connecting shaft)
16. Dimension of Penstock
17. Design flow rate
18. Protection relays installed.

The data collected from each utility are presented below (Table 3).

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b. PID: Proportional-Integral-Differentiative

Table 3. Data collected from case study partners.

List of data		Utilities				
		AM	BR	HO	BO	DE
1	Mode of operation	Run-of-river	Run-of-river	Run-of-river	Run-of-river	Run-of-river with reservoir storage of 109-acre ft, Elev 2009
2	Turbine capacity	4 units (2.2 MW, 1 MW, 2 x 0.8 MW: 4.8 MW	5 MW	0.5 MW	7 MW	5.117 MW
3	Turbine type	1 Kaplan, 3 Francis	2 Kaplan, 3 Francis	Kaplan[c]	5 Francis	Kaplan
4	Synchronous generator capacity	4.85 MW	Not available	0.57 MW	7.3 MW	5.06 MVA, 0.85 pf
5	Operating head	20-22 ft	20 ft	20.5 ft	15-24 ft	48 ft
6	Water time constant	Unknown	Unknown	Unknown	Unknown	Unknown
7	Wicket gate control	Open-close	Open-close	Unknown	Unknown	Unknown
8	Hydro governor model	Not available	Not available	SEAMTEC turbine control	Woodward type[d]	Voith hydraulic unit 1800-2000 psi
9	Type of governor control valve	None	None	Open-close	Open-close	Proportional valves, closed loop
10	Hydro governor type	None	None	Digital	Analog/manual input	Analog
11	Hydro governor PID settings	None	None	Present but not accessible	None	Voith designed logic, closed loop[e]
12	Excitation type and control	Not provided	DC, manually controlled	Basler excitation control	Solid-state DC drive, manually	Shunt static exciter. Silicon-

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c. Vertical and double regulated

d. Woodward governor at the South plant and hydraulic gate positioner at the North plant. In its early history, the South plant was load-following which was facilitated by the Woodward Governors.

e. Gate to blade positions based on Cam curves and head level

List of data		Utilities				
		AM	BR	HO	BO	DE
					controlled potentiometer[f]	controlled rectifier (SCR) output with a sensing input
13	Guide vane sensors	Present	None	Present	None	None
14	Generator damping coefficient	Unknown	Unknown	Unknown	Unknown	Unknown
15	Plant aggregate inertia	Unknown	Unknown	Unknown	Unknown	Unknown
16	Penstock dimension	Not applicable	Upper shaft[g]: 17 ft x 20 ft x 32 ft. Lower shaft: 11 ft long x 11 ft at runner and 12 ft at exit	Not available	Not applicable	16 ft Dia x 116 ft long
17	Design flow rate	Unknown	Unknown	332 ft^3/s	Unknown	1760 ft^3/s
18	Protection relays	51V, 47, [36]81 U, 86[h], 59	25, GE489[i], GE SR745[j]	25, 59, 27, 81 O-U, 32, 32R/F[k], 46, 40Q, 50, 11, 27/59, 51V, 49, 24, 56	Not provided	27/59, 48, 71[l], 77, 49[m], 26, 63

In the sections that follow, each utility is examined, and changes needed to make the plants black start capable are given in Table 4, Table 5, Table 6, and Table 7, and Table 8 for utility AM, BR, HO, BO, and DE, respectively.

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f. North plant has some automatic load following adjustment capability but has the option to use full manual control.

g. Water level typically does not exceed 24 ft in the upper shaft

h. Lockout relay: serves as an intermediary element between one or multiple relays

i. GE SR489: Generator protection relay

j. GE SR745: Transformer protection relay

k. 32 R/F: Reverse power relay

l. Main transformer oil level

m. Winding temperature relay

3.1. AM Utility Assessment

Overview: An evaluation of the data provided shows that AM utility will be able to black start if major upgrades are carried out, and system parameters critical for studying plant's response (under black start and standalone conditions) are provided. Enhancing plant's flexibility during black start requires that the wicket gate must be upgraded to a variable (e.g., proportional) type; at least a proportional-based hydro governor control must be installed, and its parameters should be accessible for tuning; an excitation system is required, and this should be capable of supporting black start; and the system protection should be upgraded for minimum protection (see Section 2.3). Furthermore, the utility must be able to provide plant aggregate inertia, water time constant, flow rate, and hydro governor type and model. These will help to accurately model and study plant's response under black start and isolated conditions. Also, it allows conducting stability analysis to determine stable control parameters and performing simulations and hardware-in-the-loop testing to derisk operation.

A detailed evaluation is given below (Table 4).

Table 4. Evaluation of AM Utility.

AM Utility Assessment		
Data requested	Data provided	Notes and changes required for black start
Mode of operation	Run-of-river	Since reservoir is absent, it is important to consider the impact of water level (or flow rate) on the generation of the hydro units. This provides insight on the load carrying capacity of the plant for the period of the year black start is to be performed. See also the comments below under "Installed capacity" for additional limitations on the load carrying capacity of a small hydro unit when black starting and forming standalone grids.
Installed capacity	Turbine capacity: 4 units (2.2 MW, 1 MW, 2 x 0.8 MW): 4.8 MW Generator capacity: 4.85 MW	Since the turbine capacity is slightly lower than that of the generator, the turbine determines the actual installed capacity of the plants (i.e., 4.8 MW). The largest unit, which in this case is the 2.2 MW, should be used to start (form) the grid, while the 1 MW, 2 x 0.8 MW can be connected afterward to contribute to load carrying capacity. Using the largest unit to start the grid is advantageous as this provides better load-frequency support than starting with the smaller units. Previous study (see Figure 14 of [36]) has shown that when a small hydro unit starts a grid and supports standalone operation, its load carrying capacity may reduce to about 65 % of its full capacity. That is, it may not be loaded beyond 65 % of its installed capacity as exceeding this can lead to instability. So, a 2.2 MW plant may support up to 1.43 MW load, and a combined capacity of 4.85 MW may carry up to a 3.12 MW load. The plant can be loaded to its installed capacity by adding battery storage, as demonstrated in Figure 14 of [36]. The power converter (inverter) used by the battery storage should have a rating at least the size of the step at which loads will be restored during the black start. E.g., if the load step is 0.3 MW, the battery storage inverter rating should be at least 0.3 MW. If the battery storage is grid-following, it should be brought online after the 2.2 MW unit must have successfully started (formed) the

AM Utility Assessment		
		grid. If the battery storage grid-forming (i.e., can form a grid), then there should be proper synchronization between the battery storage and the 2.2. MW unit used to start the grid, otherwise there may be synchronization issues.
Turbine type	1 Kaplan, 3 Francis	The turbines should be run at flow rates that maximize efficiency. This is important for maximizing the load carrying capacity of the plant, which contributes to improving its load-frequency stability. The turbine manufacturer's manual should be consulted for additional details.
Operating head	20-22 ft	Note that the operating head can (and does) vary. Selected tuning parameters (e.g., governor PID settings) should be stable for the range of possible heads which may be present during black start. Where possible, the turbines should be run at heads that maximize the load carrying capacity of the plant, as this contributes to improving its load-frequency stability.
Water time constant	Unknown	Water time constant is required for black start and isolated operation. Water time constant is dependent upon water channel characteristics as well as operating head. It may be appropriate to model the plant's power output during rapid gate movement. Providing the water time constant allows to compute nominal hydro governor PID settings (see, e.g., [37]) which can serve as the starting point of numerical investigations (i.e., dynamical simulations and stability analysis) that allow to determine tuning parameters (e.g., governor PID settings) for which the plant's operation is stable.
Wicket gate control	Open-close	Proportional wicket gate control is desirable for black start and isolated operation. It is beneficial that the wicket gates control has some proportional control. This provides flexibility in controlling the generation of the plant during black start.
Hydro governor model	Not available	The hydro governor model is required for relevant analysis of the black start and standalone operation. Identifying the hydro governor model is important for accurate modeling and simulations, which are required for determining stable tuning parameters (e.g., governor PID settings).
Type of governor control valve	None	Governor control is required for black start and standalone operation. A hydro governor must be installed if a successful black start and standalone operation must be achieved. At the minimum, proportional governor control must be installed in all the hydro units. This gives the plants load-following capabilities, i.e., the capability to automatically vary their generation (i.e., plants' power output) according to the load demand. This capability is required for forming isolated grids.
Hydro governor type	None	Digital governors are increasingly preferred over analog types. Digital governors provide more functionalities and can be easily reconfigured to suit black start and islanded operations.

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Hydro governor PID settings	None	Hydro governor settings are required for black start and isolated operation. A hydro governor is required, and its settings (PID settings) must be accessible for tuning. At the minimum, a proportional governor control should be installed in each of the hydro units. Dynamical simulations and stability analysis should be run to determine stable PID settings under black start and isolated conditions. Ensure these settings apply to all operating conditions. Generally, PID settings are usually smaller for black start and isolated operation than for when the hydro units are grid connected. As already mentioned, operating head can (and does) vary. Selected tuning parameters should be stable for the range of possible heads that may be present during black start. The response of the governor/generator system is dependent on the tuning parameters and physical characteristic of the generator and water column dynamics. Note that if only one hydro unit is used for black start and standalone operation, the integrator of the PID can be used with the proportional part. This results in isochronous operation and allows the plant to regulate the frequency to its nominal value after every instance of (load) disturbance. However, if at least two hydro units are used to operate the standalone grid, then it is highly recommended that only the proportional part of the PID is used in each plant. This allows the hydro units to (automatically) share load without communication links and prevents the plants from being overloaded. The size of the proportional gains should be set inversely proportional to the capacity of the plants. E.g., the 2.2 MW unit will have a proportional gain smaller than that of the 1 MW unit. On the contrary, if the integrator of the PID is used in each unit, this will prevent load from being shared among the generators, and this can lead to system overload. Also, this can make the units conflict with each other during frequency regulation, which can result in desynchronization and ultimate collapse of the isolated grid.
Excitation type and control	Not provided	A reliable excitation system is required for black start and isolated operation. Identifying the excitation type helps to perform thorough numerical investigations involved for determining system response and stable tuning parameters. A healthy and long-lasting battery should be used to power the excitation system of the plants. The battery should be in good condition and capable of supporting black start and providing power to auxiliary circuits. This is important as without a reliable DC source the black start may not be successful. If an AC generator is used to power the excitation system, then the rectifier (that generates the DC signal) should be in good condition and capable of supporting black start and providing power to auxiliary circuits.

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		See also the discussion in Section 2.2 above.
Guide vane sensors	Present	Guide vane sensors provide more flexibility during black start, and it is advantageous that AM already has this installed in its system. High fidelity gate and guide vane sensors help to prevent over/under estimation of dam head and flow rate. This is important for the proper control and stable operation of the plants.
Generator damping coefficient	Unknown	Providing the generator damping coefficient enhances the accurate modeling of the plant, which is used in numerical analysis performed for the black start and islanded operation to determine system response and stable tuning parameters.
Plant aggregate inertia	Unknown	Plant aggregate inertia is required for numerical analysis associated with the black start and isolated operation. The inertia is required for the numerical investigations that will be performed to determine system response and stable tuning parameters, as discussed above under "Hydro governor PID settings." Inertia can be calculated using the mass and radius of rotating components of the generator and turbine.
Design flow rate	Unknown	It is useful for determining flow rates where the turbine efficiency is high. See also the discussion under "Turbine type" above.
Protection relays	51V, 47, 81 U, 86, 59	The existing protection relays should be upgraded to those identified in Section 2.3 for minimum protection during black start and isolated operation. This upgrade is important so that the generators, transformers, and other electrical equipment are well protected during black start and standalone operation. If the 2.2 MW is used to start (form) the grid, as already mentioned in Table 1 under "25 sync-check relay," the sync-check relay for the plant must be configured to allow connection on a dead bus. This is important as contrary to grid-connected operation, the external grid is not present to provide the live (hot) bus that the plant's breaker can close on. Afterward, the sync-check relay used by the remaining hydro units can then be configured to allow the plant's breakers to close on hot buses, since the 2.2. MW plant must have formed the grid and energized the buses. See Section 2.3 and *Table 1* above for more details on the protections being recommended for black start and isolated operation.

3.2. BR Utility Assessment

Overview: An assessment of the data collected indicates that BR utility will be able to black start if major upgrades are done, and critical system parameters are provided to study plant's response under black start and isolated conditions. Increasing plant's flexibility during black start demands that the wicket gate is replaced with a variable (e.g., proportional) type; at the minimum a proportional-based hydro governor control must be installed, and its parameters should be accessible for tuning; a guide vane sensor should be installed; and the protection system should be upgraded for minimum protection. As to system parameters, the utility should be able to supply plant aggregate inertia, water time constant, flow rate, and hydro governor type and model. These facilitate accurate modeling of the plant, conducting stability analysis to determine stable controller settings, and performing simulations and hardware-in-the-loop testing to derisk and ensure stable operation.

A more detailed assessment is discussed below (Table 5).

Table 5. Evaluation of BR Utility.

BR Utility Assessment		
Data requested	Data provided	Notes and changes required for black start
Mode of operation	Run-of-river	Due to limited or no water storage, it is important to consider the impact of water level (or flow rate) on the generation of the hydro units. This provides insight on the load carrying capacity of the plant for the period of the year black start is to be performed. See also the comments below under "Installed capacity" for additional limitations on the load carrying capacity of a small hydro unit when black starting and forming standalone grids.
Installed capacity	Turbine capacity: 5 MW Generator capacity: Not available	If the turbine capacity is greater than that of the generator, then the generator determines the installed capacity of the plant, otherwise, the turbine determines the installed capacity of the plant. The largest unit should be used to start (form) the grid, while the smaller units can be connected afterward to increase load carrying capacity. Using the largest unit to start the grid is advantageous as this provides better load-frequency support than starting with the smaller units. Previous study (see Figure 14 of [36]) shows that when a small hydro unit starts a grid and supports standalone operation, its load carrying capacity may reduce to about 65 % of its full capacity. That is, it may not be loaded beyond 65 % of its installed capacity as exceeding this can lead to instability. So, the 5 MW capacity may support up to 3.25 MW of load. The plant can be loaded to its installed capacity by adding battery storage, as demonstrated in Figure 14 of [36]. The power converter (inverter) used by the battery storage should have a rating at least the size of the step at which loads will be restored during the black start. E.g., if the load step is 0.5 MW, the battery storage inverter rating should be at least 0.5 MW. If the battery storage is grid-following, it should be brought online after the largest unit must have successfully formed the grid. If the battery storage is grid-forming, then the battery storage should be properly synchronized with the largest hydro unit used to start the grid, otherwise there may be synchronization issues.
Turbine type	2 Kaplan, 3 Francis	The turbines should be run at flow rates that maximize efficiency. This is important for maximizing the load carrying capacity of the plant, which contributes to improving its load-frequency stability. The turbine manufacturer's manual should be consulted for additional details.

BR Utility Assessment		
Operating head	20 ft	Note that head can vary. Selected tuning parameters (e.g., governor PID settings) should be stable for the range of heads that may be encountered during black start. Where possible, the turbines should be run at heads that maximize the load carrying capacity of the plant, as this contributes to improving its load-frequency stability.
Water time constant	Unknown	Water time constant is required for black start and isolated operation. Water time constant is dependent upon water channel characteristics as well as operating head. It may be appropriate to model the plant's power output during rapid gate movement. Providing the water time constant allows to compute nominal hydro governor PID settings (see, e.g., [37]) which can serve as the starting point of numerical investigations (i.e., dynamical simulations and stability analysis) that allow to determine parameters (e.g., governor PID settings) for which the plant's operation is stable.
Wicket gate control	Open-close	Proportional wicket gate control is desirable for black start and isolated operation. It is desirable that the wicket gates control has some proportional control. This provides flexibility in controlling the generation of the plant during black start.
Hydro governor model	Not available	The hydro governor model is required for relevant analysis of the black start and standalone operation. Identifying the hydro governor model is important for accurate modeling and simulations, which are required for determining stable tuning parameters (e.g., governor PID settings).
Type of governor control valve	None	Governor control is required for black start and standalone operation. A hydro governor control must be installed if a successful black start and standalone operation must be achieved. At the minimum, a proportional governor control valve should be installed in all the hydro units. This gives the plants load-following capabilities, i.e., the capability to automatically vary their power output according to the load demand. This capability is required for starting and forming standalone grids.
Hydro governor type	None	Digital governors are increasingly preferred over analog types. Digital governors provide more functionalities and can be easily reconfigured to suit black start and isolated operations.
Hydro governor PID settings	None	Hydro governor settings are required for black start and isolated operation. A hydro governor is required, and its settings (PID settings) must be accessible for tuning. As already mentioned, at the minimum, proportional governor control should be installed in all the hydro units. Dynamical simulations and stability analysis should be run to determine stable PID settings under black start and isolated

BR Utility Assessment		
		conditions. Ensure these settings apply to all operating conditions. Generally, PID settings are usually smaller for black start and isolated operation than for when the hydro units are grid connected. As previously mentioned, operating head can vary. Selected tuning parameters should be stable for the range of possible heads that may be present during black start. The response of the governor/generator system is dependent on the tuning parameters and physical characteristic of the generator and water column dynamics. Note that if only one hydro unit is used for black start and standalone operation, the integrator of the PID can be used with the proportional part. This results in isochronous operation and means that the plant will regulate the frequency to its nominal value after every instance of (load) disturbance. However, if at least two hydro units are used to operate the standalone grid, then it is highly recommended that only the proportional part of the PID is used in each plant. This allows the hydro units to (automatically) share load without communication links and prevents the units from being overloaded. The size of the proportional gains should be set inversely proportional to the capacity of the plants. E.g., a 2 MW unit will have a proportional gain smaller than that of the 1 MW unit. On the contrary, if the integrator of the PID is used in each unit, this will prevent load from being shared among the units, and this can lead to system overload. Also, this can make the units conflict with each other during frequency regulation, which can result in desynchronization and ultimate collapse of the isolated grid.
Excitation type and control	DC, manually controlled	The exciter should be capable of supporting black start and isolated operation. A healthy and long-lasting battery should be used to power the excitation system of the plants. The battery should be in good condition and capable of supporting black start and providing power to auxiliary circuits. This is important as without a reliable DC source the black start may be unsuccessful. If an AC generator is used to power the excitation system, then the rectifier (that generates the DC signal) should be in good condition and capable of supporting black start and providing power to auxiliary circuits. Also, identifying the excitation type helps to perform thorough numerical investigations involved for determining system response and stable tuning parameters. See also the discussion in Section 2.2 above.
Guide vane sensors	None	Guide vane sensors provide additional flexibility during black start. High fidelity gate and guide vane sensors help to prevent over/under estimation of dam head and flow rate. This is important for the proper control and stable operation of the plants.

BR Utility Assessment		
Generator damping coefficient	Unknown	Providing the generator damping coefficient enhances the accurate modeling of the plant, which is used in numerical analysis performed for the black start and islanded operation to determine system response and stable tuning parameters.
Plant aggregate inertia	Unknown	Plant aggregate inertia is required for numerical analysis associated with the black start and isolated operation. Computing the plant inertia enhances the accurate modeling of the plant, and successfully performing numerical investigations that help to determine system response and stable tuning parameters, as discussed above under "Hydro governor PID settings." Inertia can be calculated using the mass and radius of rotating components of the generator and turbine.
Penstock dimension	Upper shaft: 17 ft x 20 ft x 32 ft. Lower shaft: 11 ft long x 11 ft at	It is useful for computing flow rates where the turbine efficiency is high. See also the discussion under "Turbine type" above.
Protection relays	25, GE489, GE SR745	The existing protection relays should be upgraded to provide at least all the protections highlighted in Section 2.3 for black start and isolated operation. If the largest hydro unit is used to start (form) the grid, as already discussed in Table 1 under "25 sync-check relay," the sync-check relay for the plant must be configured to allow connection on a dead bus. This is important as contrary to grid-connected operation, the external grid is not present to provide the live (hot) bus that the plant's breaker can close on. The sync-check relay used by the remaining hydro units can then be configured to allow the plant's breaker to close on a hot bus, since the largest hydro unit must have formed the grid and energized the buses. See Section 2.3 and Table 1 above for more details on the protections being recommended, which are important for black start and isolated operation.

3.3. HO Utility Assessment

Overview: Assessing the data collected reveals that HO utility should be able to black start with minor upgrade and providing parameters necessary for studying plant's response under black start and standalone operations. The upgrade involves installing a variable (i.e., a proportional) type wicket gate to enhance the plant's flexibility during black start. The utility must be able to provide plant aggregate inertia, water time constant, flow rate, and hydro governor model. These help to accurately model the plant, conduct stability analysis to determine stable controller settings, and perform simulations and hardware-in-the-loop testing to derisk and ensure stable operation.

A detailed assessment can be found below (Table 6).

Table 6. Evaluation of HO Utility.

HO Utility Assessment		
Data requested	Data provided	Notes and changes required for black start
Mode of operation	Run-of-river	Due to the absence of reservoir, the impact of water level (or flow rate) on the hydro unit generation should be considered. This provides insight on the load carrying capacity of the plant for the period of the year black start is to be performed. See also the comments below under "Installed capacity" for additional limitations on the load carrying capacity of a small hydro unit when black starting and forming isolated grids.
Installed capacity	Turbine capacity: 0.5 MW Generator capacity: 0.57 MW	Since the capacity of the turbine generator is less than that of the generator, the turbine determines the installed capacity of the plant (i.e., 0.5 MW). Previous study (see Figure 14 of [36]) shows that when a small hydropower plant starts a grid and supports standalone operation, its load carrying capacity may reduce to about 65 % of its full capacity. This means that it may not be loaded beyond 65 % of its installed capacity as exceeding this can lead to instability. So, the 0.5 MW capacity may support up to .325 MW of load. The plant can be loaded to its installed capacity by adding battery storage, as demonstrated in Figure 14 of [36]. The power converter (inverter) used by the battery storage should have a rating at least the size of the step at which loads will be restored during the black start. For example, if the load step is 0.1 MW, the battery storage inverter rating should be at least 0.1 MW. If the battery storage is grid-following, it should be brought online after the hydro unit must have successfully formed the grid. If the battery storage is grid-forming, then the battery storage should be properly synchronized with the plant, otherwise there may be synchronization issues.
Turbine type	1 Kaplan	The turbine should be run at flow rates that maximize efficiency. This is important for maximizing the load carrying capacity of the plant, which contributes to improving its load-frequency stability. The turbine manufacturer's manual should be consulted for additional details.
Operating head	20.5 ft	Note that head can vary. Controller parameters (e.g., governor PID settings) should be stable for the range of heads that may be present during black start. Where possible, the turbine should be run at heads that maximize the load carrying capacity of the plant, as this contributes to improving its load-frequency stability.
Water time constant	Unknown	Water time constant is required for black start and isolated operation. Water time constant is dependent upon water channel characteristics as well as operating head. It may be appropriate to model the plant's power output during rapid gate movement.

HO Utility Assessment		
		Providing the water time constant allows to compute nominal hydro governor PID settings (see, e.g., [37]) which can serve as the starting point of numerical investigations (i.e., dynamical simulations and stability analysis) that allow to determine parameters (e.g., governor PID settings) for which the plant's operation is stable.
Wicket gate control	Unknown	Proportional wicket gate control is desirable for black start and isolated operation. It is desirable that the wicket gates have some proportional control. This provides flexibility in controlling the generation of the plant during black start.
Hydro governor model	SEAMTEC turbine control	Hydro governor model is required for relevant analysis of the black start and standalone operation. Identifying the hydro governor model is important for accurate modeling and simulations, which are required for determining stable tuning parameters (e.g., governor PID settings).
Type of governor control valve	Open-close	A variable governor control is required for black start and standalone operation. At the minimum, a proportional governor control valve should be installed. This allows varying the response of the plant to suit black start. Also, it provides the plant with load-following capabilities, i.e., the capability to vary power output based on the load demand. This capability is required for starting and forming standalone grids.
Type of hydro governor	Digital	Having a digital governor is a plus. Digital governors provide more functionalities and can be easily reconfigured to suit black start and standalone operations.
Hydro governor PID settings	Present but not accessible	Hydro governor settings need to be accessible. The hydro governor PID settings need to be accessible so they can be tuned for stable operation during black start and islanded operations. The PID settings are required for dynamic simulations and stability analysis that may be carried out to determine stable settings for black start and isolated conditions. These settings should apply to all operating conditions. Generally, PID settings are usually smaller for black start and isolated operation than for when the hydro units are grid connected. As previously mentioned, operating head can vary. Selected tuning parameters should be stable for the range of heads that may be present during black start. The response of the governor/generator system is dependent on the tuning parameters and physical characteristic of the generator and water column dynamics. Since HO uses only one hydro unit, it is safe to include the integrator of the PID control during black start and standalone operation. This results in isochronous operation and allows the plant to regulate the frequency to its nominal value after every instance of (load) disturbance.

HO Utility Assessment		
		However, if at least two hydro units were used to operate the standalone grid, then it is highly recommended that only the proportional part of the PID is used in each plant. This allows the hydro units to (automatically) share load without communication links and prevents the plants from being overloaded. The size of the proportional gains should be inversely proportional to the capacity of the plants. E.g., a 1 MW unit will have a proportional gain smaller than that of the 0.5 MW unit. On the contrary, if the integrator of the PID is used in each unit, this will prevent load from being shared among the generators, and this can lead to system overload. Also, this can make the units conflict with each other during frequency regulation, and this can lead to desynchronization and ultimate collapse of the grid.
Excitation type and control	Basler excitation control	The exciter should be capable of supporting black start and isolated operation. A healthy and long-lasting battery should be used to power the excitation system. The battery should be in good condition and capable of supporting black start and providing power to auxiliary circuits. This is important as without a reliable DC source the black start may be unsuccessful. If an AC generator is used to power the excitation system, then the rectifier (that generates the DC signal) should be in good condition and capable of supporting black start and providing power to auxiliary circuits. Also, identifying the excitation type helps to perform thorough numerical investigations involved for determining system response and stable tuning parameters. See also the discussion in Section 2.2 above.
Guide vane sensors	Present	The presence of the guide vane sensors is a plus. High fidelity gate and guide vane sensors help to prevent over/under estimation of dam head and flow rate. This is important for the proper control and stable operation of the plant.
Generator damping coefficient	Unknown	Providing generator damping coefficient enhances the accurate modeling of the plant, which is used in numerical analysis performed for black start and islanded operation to determine system response and stable tuning parameters.
Plant aggregate inertia	Unknown	Plant aggregate inertia is required for numerical analysis associated with the black start and isolated operation. Computing the plant inertia enhances the accurate modeling of the plant, and successfully performing numerical investigations that help to determine system response and stable tuning parameters, as discussed above under “Hydro governor PID settings.” Inertia can be computed using the mass and radius of rotating components of the generator and turbine.
Design flow rate	332 ft^3/s	Flow rate may vary, which in turn can affect the turbine efficiency. See also the discussion under “Turbine type” above.

HO Utility Assessment		
Protection relays	25, 59, 27, 81 O-U, 32, 32R/F, 46, 40Q, 50, 11, 27/59, 51V, 49, 24, 56	HO's protection is adequate and covers most of the protection discussed in Section 2.3. A minimal upgrade will be required, which involves installing the 87G, 87T, 64S, 64 F, 60, and 78 relays. As already mentioned in Table 1 under "25 sync-check relay," the sync-check relay of the plant must be configured to allow connection on a dead bus. This is important as contrary to grid connected operation, the external grid is not present to provide the live (hot) bus that the plant's breaker can close on. See Section 2.3 and Table 1 above for more details on the list of relays and recommendations provided.

3.4. BO Utility Assessment

Overview: Evaluating the data provided indicates that BO utility will be able to black start if major upgrades are carried out and the utility provides parameters necessary for studying plant's response under black start and standalone operation. Enhancing plant's flexibility during black start demands that a wicket gate is installed, and this should be of a variable (e.g., proportional) type; a digital-type proportional-based hydro governor control may be preferred, and its parameters should be accessible for tuning; and the system protection should be upgraded for minimum protection (see Section 2.3). Furthermore, the utility must be able to provide plant aggregate inertia, water time constant, flow rate, and hydro governor type and model. These allow to accurately model and study plant's response under black start and isolated conditions, conduct stability analysis to determine stable controller settings, and perform simulations and hardware-in-the-loop testing to derisk operation.

A detailed assessment is given found below (Table 7).

Table 7. Evaluation of BO Utility.

BO Utility Assessment		
Data requested	Data provided	Notes and changes required for black start
Mode of operation	Run-of-river	Due to the absence of reservoir, the impact of water level (or flow rate) on the hydro unit generation should be considered. This provides insight on the load carrying capacity of the plant for the period of the year black start is to be performed. See also the comments below under "Installed capacity" for additional limitations on the load carrying capacity of a small hydro unit when black starting and forming isolated grids.
Installed capacity	Turbine capacity: 7 MW Generator capacity: 7.3 MW	Since the turbine capacity is less than that of the generator, then the turbine determines the installed capacity of the plant (i.e., 7 MW). Our previous studies (see Figure 14 of [36]) show that when a small hydropower plant forms a standalone grid, its load carrying capacity may reduce to about 65 % of its full capacity. This implies that it may not be loaded beyond 65 % of its installed capacity as exceeding this can lead to instability. So, the 7 MW capacity may support a load up to 4.55 MW.

		The plant can be loaded to its installed capacity by adding battery storage, as demonstrated in Figure 14 of [36]. Also, the use of battery storage helps to improve the response and load-frequency stability of the plant. The power converter (inverter) used by the battery storage should have a rating at least the size of the step at which loads will be restored during the black start. For instance, if the suitable load step is 0.5 MW, the battery storage inverter rating should be at least 0.5 MW. If the battery storage is grid-following, it should be brought online after the hydro unit must have successfully formed the grid. If the battery storage is grid-forming, then the battery storage should be properly synchronized with the plant, otherwise there may be synchronization issues.
Turbine type	5 Francis	The turbines should be run at flow rates that maximize efficiency. This is important for maximizing the load carrying capacity of the plant, which contributes to improving its response and load-frequency stability. The turbine manufacturer's manual should be consulted for additional details.
Operating head	15-24 ft	Operating head do vary. The governor settings (e.g., the governor PID settings) should be stable for the range of heads that may be present during black start. Where possible, the turbine should be run at heads that maximize the load carrying capacity of the plant, as this contributes to improving its load-frequency stability.
Water time constant	Unknown	Water time constant is required for analysis associated with black start and standalone operation. Water time constant is dependent upon water channel characteristics as well as operating head. Providing the water time constant allows to compute nominal hydro governor PID settings (see, e.g., [37]) which can serve as the starting point of numerical investigations (i.e., dynamical simulations and stability analysis) that allow to determine parameters (e.g., governor PID settings) for which the plant's operation is stable.
Wicket gate control	Unknown	Flexibility is required in the wicket gate control during black start and isolated operation. Proportional wicket gate control is desirable. This provides flexibility in controlling the generation of the plant during black start and isolated operation.
Hydro governor model	Woodward type	Hydro governor model is required for relevant analysis of the black start and standalone operation. Providing the mathematical model of the Woodward turbine will facilitate accurate modeling and simulations, which are required for determining tuning parameters (e.g., governor PID settings) that support stable operation during black start.
Type of governor control valve	Open-close	A variable governor control (i.e., with PID settings) is required for black start and standalone operation.

		At the minimum, a proportional governor control valve should be installed in all the units. This provides the hydro units with load-following capability and allows them to share load during the standalone operation. This capability is required for black starting and maintaining standalone operations. It will be a plus if the load-following control of the South plant's governor is still operational. With this capability in place, the South plant can be used to start (form) the grid, and this will also require the plant to have a functioning gate positioner to adjust the water flowing into the generating unit. The other hydro units can be connected afterward but these also should have proportional governor control installed to facilitate power sharing among the units. This helps to prevent system overload.
Type of hydro governor	Analog/Manual input	Having a digital governor is a plus. Digital governors provide more functionalities and can be easily reconfigured to settings that support black start and standalone operations.
Hydro governor PID settings	None	Hydro governor needs to have PID settings, and these must be accessible for tuning. The hydro governor needs to have PID control installed, and its settings must be accessible so they can be tuned for stable operation during black start and islanded operations. Dynamical simulations and stability analysis should be run to determine stable PID settings under black start and isolated conditions. Ensure these settings apply to all operating conditions. Generally, PID settings are usually smaller for black start and isolated operation than for when the hydro units are grid connected. As previously mentioned, operating head can vary. Selected tuning parameters should be stable for the range of heads that may be present during black start. The response of the governor/generator system is dependent on the tuning parameters and physical characteristic of the generator and water column dynamics. Note that if only one hydro unit is used for black start and standalone operation, the integrator of the PID can be used with the proportional part. This results in isochronous operation and means that the plant will regulate the frequency to its nominal value after every instance of (load) disturbance.

		However, if at least two hydro units are used to operate the standalone grid, then it is highly recommended that only the proportional part of the PID is used in each plant. This allows the hydro units to (automatically) share load without communication links and prevents the units from being overloaded. The size of the proportional gains should be set inversely proportional to the capacity of the plants. E.g., a 425 kW unit will have a proportional gain smaller than that of the 350 kW unit. On the contrary, if the integrator of the PID is used in each unit, this will prevent load from being shared among the units, and this can lead to system overload. Also, this can make the units conflict with each other during frequency regulation, which can result in desynchronization and ultimate collapse of the isolated grid.
Excitation type and control	Solid-state DC drive, manually controlled potentiometer	The exciter should be capable of supporting black start and isolated operation. If an AC generator is used to power the excitation system, then the solid-state rectifier (that generates the DC signal) should be in good condition and capable of supporting black start and providing power to auxiliary circuits. If a battery is used to power the excitation system, then the battery should be healthy and long-lasting. The battery should be in good condition and capable of supporting black start and providing power to auxiliary circuits. This is important as without a reliable DC source the black start may be unsuccessful. Also, identifying the excitation type helps to perform thorough numerical investigations involved for determining system response and stable tuning parameters. See also the discussion in Section 2.2 above.
Guide vane sensors	None	The presence of the guide vane sensors is a plus. High fidelity gate and guide vane sensors help to prevent over/under estimation of dam head and flow rate. This is important for the control of power generated by the plant, which also contributes to the stable operation of the plant.
Generator damping coefficient	Unknown	Providing the generator damping coefficient enhances the accurate modeling of the plant, which is used in numerical analysis performed for the black start and islanded operation to determine system response and stable tuning parameters.
Plant aggregate inertia	Unknown	Plant aggregate inertia is required for numerical analysis associated with the black start and isolated operation. Computing the plant inertia enhances the accurate modeling of the plant, and successfully performing numerical investigations that help to determine system response and stable tuning parameters, as discussed above under “Hydro governor PID settings.” Inertia can be calculated using the mass and radius of rotating components of the generator and turbine.
Design flow rate	Unknown	It is desirable to determine the flow rates where the turbine efficiency is maximized. See also the discussion under “Turbine type” above.

Protection relays	Not provided	Adequate protection is required during black start and standalone operation. The minimal protection identified in Section 2.3 should be provided. As already mentioned in Table 1 under “25 sync-check relay,” the sync-check relay of the plant forming (starting) the grid should be reconfigured to allow connection on a dead bus. This is important as contrary to grid-connected operation, the external grid is not present to provide the live (hot) bus that the plant’s breaker can close on. See Section 2.3 and Table 1 above for more details on the protections being recommended.

3.5. DE Utility Assessment

Overview: An evaluation of the data collected shows that DE utility will be able to black start if minor upgrade is done, and system parameters critical for studying plant’s response (under black start and standalone conditions) are made available. The upgrade would involve installing a variable (i.e., a proportional) type wicket gate to enhance plant’s flexibility during black start. The utility must be able to provide plant aggregate inertia, water time constant, flow rate, and hydro governor model. These help to accurately model the plant, conduct stability analysis to determine stable controller settings, and perform simulations and hardware-in-the-loop testing to derisk and ensure stable operation.

A detailed assessment is given below (Table 8).

Table 8. Evaluation of DE Utility.

DE Utility Assessment		
Data requested	Data provided	Notes and changes required for black start
Mode of operation	Run-of-river	The impact of water level (or flow rate) on the hydro unit generation should be evaluated to ascertain the load carrying capacity of the plant for the period of the year black start is to be performed. See also the comments below under “Installed capacity” for additional limitation on the load carrying capacity of a small hydropower plant when black starting and forming standalone grids.
Installed capacity	Turbine capacity: 5.117 MW Generator capacity: 5.06 MW	Since the turbine capacity slightly exceeds that of the turbine, the hydropower plants may not be loaded beyond the capacity of the generator (i.e., 5.06 MW). Previous studies (see Figure 14 of [36]) have shown that when a small hydropower plant forms an isolated grid, its load carrying capacity may reduce to about 65 % of its full capacity. Exceeding this can lead to instability. Hence, the 5.06 MW capacity may support an aggregate load up to 3.23 MW. A way the plant can be loaded to its installed capacity is by adding battery storage, as demonstrated in Figure 14 of [36]. Also, the use of battery storage helps to improve the plant’s response and stability. The rating of the power converter (inverter) used by the battery storage should be at least the size of the step at which loads will be restored during the black start. For example, if the suitable load step is 0.5 MW, the battery storage inverter rating should be at least 0.5 MW.

DE Utility Assessment		
		If the battery storage is grid-following, it should be brought online after the hydro unit must have successfully started (formed) the grid. If the battery storage is grid-forming, then the battery storage should be properly synchronized with the plant to avoid desynchronization.
Turbine type	Kaplan	The turbines should be run at flow rates that maximize efficiency. This is crucial for maximizing the load carrying capacity of the plant and improving its response and load-frequency stability. The turbine manufacturer's manual should be consulted for additional details.
Operating head	48 ft	Operating head may vary. The governor settings (e.g., the governor PID settings) should be stable for the range of heads that may be present during black start. Where possible, the turbine should be run at heads that maximize the load carrying capacity of the plant, as this contributes to improving its load-frequency stability.
Water time constant	Unknown	Water time constant is required to conduct analysis associated with black start and standalone operation. Water time constant depends on water channel characteristics as well as operating head. Providing the water time constant allows to compute nominal hydro governor PID settings (see, e.g., [37]) which can be used as the starting point of numerical investigations including dynamical simulations and stability analysis that allow to determine parameters (e.g., governor PID settings) for which the plants' operation is stable.
Wicket gate control	Unknown	A variable wicket gate control is desirable to provide flexibility during black start and standalone operation. Fitting the wicket gate with a proportional control is desirable. This provides flexibility in controlling the generation of the plant during black start and isolated operation.
Hydro governor model	Voith hydraulic unit 1800-2000 psi	Hydro governor model is required for numerical investigations relevant for black start and standalone operation. Having the mathematical model of the Voith hydraulic unit will facilitate accurate modeling and simulations of the black start and standalone scenarios, which are required for determining stable tuning parameters (e.g., governor PID settings) for black start and standalone operation.
Type of governor control valve	Proportional valves, closed loop	The presence of the proportional governor valves is a plus. Generally, a proportional governor control valve should at the minimum be installed in all the hydro units. This allows the hydro units to share load during standalone operation. This capability is required for black start and standalone operations.
Type of hydro governor	Analog	Digital governors provide additional flexibility. Digital governors provide more functionalities and are easy to reconfigure to settings that support stable operations during black start and standalone operations.

DE Utility Assessment		
Hydro governor PID settings	Voith designed logic, closed loop	Hydro governors’ proportional (or PID) settings should be accessible for tuning. The hydro governors’ proportional (or PID) settings must be accessible for tuning to support black start and islanded operations. Dynamical simulations and stability analysis should be run to determine stable proportional (or PID) settings under black start and isolated conditions. These settings should apply to all operating conditions. Generally, PID settings are usually smaller for black start and isolated operation than for when the hydropower plants are grid connected. As already mentioned, operating head may vary. The tuning parameters selected should be stable for the range of heads that may be present during black start. The response of the governor/generator system is dependent on the tuning parameters and physical characteristic of the generator and water flow rate. Since the hydro units have proportional valves, there is a guarantee that when multiple hydro units are operated, they will share load without communication links. The size of the proportional gains should be set inversely proportional to the capacity of the plants. E.g., a 4.3 MW unit will have a proportional gain smaller than that of the 0.76 MW unit. Should the hydropower be fitted with PID-based governor control, the following should be considered: If only one hydro unit is used for black start and standalone operation, the integrator of the PID can be used with the proportional part. This gives isochronous operation and implies that the plant will regulate the frequency to its nominal value after every instance of (load) disturbance. However, if at least two hydro units are used to operate the standalone grid, then it is highly recommended that only the proportional part of the PID is used in each plant. This allows the hydro units to (automatically) share load without communication links and prevents the units from being overloaded. Conversely, if the integrator of the PID is used in each unit, this will prevent load from being proportionally shared among the units, and this can cause system overload. Also, the units can conflict with each other during frequency regulation, which can lead to desynchronization and the eventual collapse of the standalone grid.
Excitation type and control	Shunt static exciter. SCR output with a sensing input	The exciter should be capable of supporting black start and standalone operations. If an AC generator is used to power the excitation system, then the solid-state rectifier (that generates the DC signal) should be in good condition and capable of supporting black start and providing power to auxiliary circuits. If a battery is used to power the excitation system, then the battery should be healthy and long-lasting. The battery should be in good condition and capable of supporting black start and providing power

DE Utility Assessment		
		to auxiliary circuits. This is important as without a reliable DC source the black start may not be successful. Also, having the excitation model aids accurate modeling and facilitate numerical investigations for determining system response and stable tuning parameters. See also the discussion in Section 2.2 above.
Guide vane sensors	None	Installing guide vane sensors is desirable for black start and islanded operation. High fidelity gate and guide vane sensors help to prevent over/under estimation of dam head and flow rate. This provides flexibility in determining the power generated by the plant, which also contributes to stable operation.
Generator damping coefficient	Unknown	Providing the generator damping coefficient enhances the accurate modeling of the plant, which is used in numerical analysis performed for the black start and islanded operation to determine system response and stable tuning parameters.
Plant aggregate inertia	Unknown	Plant aggregate inertia is required for numerical analysis associated with the black start and isolated operation. Calculating the plant inertia enhances the accurate modeling of the plant, and successfully performing numerical investigations that help to determine system response and stable tuning parameters, as discussed above under "Hydro governor PID settings." Inertia can be calculated using the mass and radius of rotating components of the generator and turbine.
Penstock dimension	16 ft Dia x 116 ft long	Computing flow rates where the turbine efficiency is high is recommended. See also the discussion under "Turbine type" above.
Design flow	1760 ft^3/s	It is desirable to determine flow rates that maximize turbine efficiency. See also the discussion under "Turbine type" above.
Protection relays	27/59, 48, 71, 77, 49, 26, 63	The protection relays can be upgraded to those identified in Section 2.3. The protection relays should be upgraded to those recommended in Section 2.3 for black start and standalone operation. As already discussed in Table 1 under "25 sync-check relay," the sync-check relay of the plant starting the grid should be reconfigured to allow connection on a dead bus. As opposed to grid-connected operation, the absence of external grid in standalone operation means that there is no live (hot) bus that the plant's breaker can close on. See Section 2.3 and Table 1 above for additional discussions on the protections being recommended.

4. RETROFIT THEMES AND COMPILED CHECKLIST

Small hydropower is well positioned as a solution to the need for black start services in rural and remote areas, driven by an increase in extreme weather and a shift toward variable renewable generation. Since rural and remote communities are often weakly connected to the rest of the grid through a single point of transmission, they can be disproportionally impacted by weather and wildfire related outages. For those communities with small hydropower plants though, there is a potential solution. Retrofitting some of the 2,198 small hydropower plants with black start capabilities can help utilities and system operators provide power to critical services during emergencies.

One of the challenges for making general recommendations to the hydropower industry is that every plant is fundamentally different. These differences can arise from turbine type, head, river species, or inflow patterns, but they ultimately translate to different operational patterns and plant capabilities. While the custom built and regulated nature of hydropower plants makes the retrofit process different for everyone, there are some themes that connect the case studies. The following five themes cut across both the previously implemented retrofits in Section 1 and the recommendations in the paper studies in Section 3, indicating that most new retrofit candidates will need to consider them.

1. **Protection needs "black start" mode:** hydropower plants that are not designed with black start capabilities will have protections that prevent them from interconnecting to a "dead bus." These protections will need to be overridden in every retrofit case and a separate black start mode should be established so that operators can safely switch between black start and grid-connected modes, minimizing the risk to the plant.
2. **Wicket gates need modern controls:** digital governors accelerate the parameter tuning process and gate position sensors improve controllability, so plants with mechanical governors should be upgraded. Furthermore, a black start and islanding mode should be established for controls to maximize plant performance.
3. **Robust excitation support:** the DC system or excitation generator needs to be reliable enough to form and sustain the rotor electromagnetic field. These systems are typically undersized in plants that were not designed for black start, so they will need to be upgraded.
4. **Turbine-governor model validation and operator training:** validation of a standard hydro governor model is needed to characterize the dynamic response (i.e., inertial and primary frequency response) of the GDH. This is required for control development and old hydropower plants often have outdated or incorrect models. Operator training is also typically required to ensure the hardware retrofits are utilized correctly during the black start process.
5. **Transformer and cranking path energization:** any upgradation and control adjustment in front of the point of interconnection will depend upon the existing interconnection. Coordination with the transmission or distribution operator may be required.

For a more thorough list of actions that need to be taken, the authors have compiled the checklists identified in Section 2. While some of these steps may have already been completed depending on the retrofit candidate plant, the checklist can help hydropower owners understand the level of effort required to prepare their specific plant for black start.

Wicket gate or nozzle flow control

- The control system can access the generator shaft speed
- The control system can access the position of the wicket gate or nozzle opening
- The wicket gate position or nozzle opening can be controlled continuously to intermediate values
- A speed control mode has been developed with appropriate PID parameters

Excitation system

- Determine AVR parameters through power flow and EMT simulation
  - Exciter rated voltage and current, field rated voltage and current

  - Ceiling voltage under no-load, loaded, and disturbance conditions
  - Excitation system time
  - Under and over excitation limiters, Volt/Hz limiter
  - VAR and power factor control systems
  - Power system stabilizer in grid-connected mode
  - Pole slipping protection

Protection system

- The existing plant protections have been accurately cataloged
- All missing protections from Table 1 have been installed to protect the hydropower plant and transformers
- There is a 25 sync-check relay that has been dedicated for black start so that the one used for grid-connected operation is not overridden or reconfigured for each black start, reducing the risk of human error and compromising system protection
- Less restrictive frequency and voltage threshold settings have been used in the 81 O-U over/under frequency and 27/59 over/under voltage relays to avoid nuisance tripping during power swings

Auxiliary power system

- Determine the total rating of the auxiliaries and duration of battery support
- Choose the desired initial and final state of charge of the battery
- Install a battery, generator, or hybrid auxiliary power system that can meet the power and energy capacity requirements of the plant

Cranking path energization

- The cranking path has been determined
- The inrush current has been determined either analytically or by simulation.
- A soft-start mechanism is in place to reduce inrush current to acceptable levels
- If a soft-start mechanism is not installed, then ensure that the inrush current magnitude does not exceed the tripping threshold of current protection relays for plant and transformer.

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Appendix A

Operational Limits of Synchronous Generators

Operation of any synchronous machine can be described using the following simple equations for active and reactive power (resistance in windings are neglected):

$$P = 3\frac{E(I_f)\cdot V}{X} sin\delta \qquad (1)$$

$$Q = 3\frac{E(I_f)\cdot V}{X} cos\delta - 3\frac{V^2}{X} \qquad (2)$$

Where P and Q are active and reactive power respectively, V is grid voltage (considered constant for simplicity); X – stator reactance; δ – is power angle; $E(I_f)$ is no load voltage as a function of excitation field current I_f. These equations can be derived from the simple model of synchronous machine shown in Figure A-1.

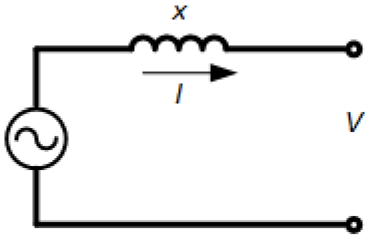

Figure A-1. Simplified representation of synchronous machine (Source: NREL).

Stability limit of synchronous machine can be defined as:

$$I(I_f) = \frac{E(I_f)}{X} \qquad (3)$$

In synchronous condenser (SC) mode, because of lack of prime mover or mechanical load, there is no active power produced or consumed (except for losses). Therefore, for SC both active power and power angle are almost equal to 0:

$$P = 0 \quad \rightarrow \quad \delta = 0 \qquad (4)$$

The reactive power and current can then be the written as

$$Q_{cond} = 3\frac{V}{X}[E(I_f) - V], \quad I_{cond} = \frac{E(I_f)-V}{X}, \quad I_{cond} \le I_{max} \qquad (5)$$

Stator current should always be kept below thermal limit of the stator determined by maximum armature current $I_{a.max}$.

Similarly, the field current I_f must also be kept below maximum allowed level $I_{f.max}$ to respect the thermal limit of machine's rotor:

$$E(I_f) \rightarrow I_f \le I_{f.max} \qquad (19)$$

Above thermal limitations in combination with non-linear no-load characteristic of synchronous machine due to magnetic saturation (example shown in Figure A-2) and excitation stability limit create non-symmetric reactive capability for any SC. Vector diagrams of an over and under-excited synchronous machine in different modes are shown in Figure A-3.

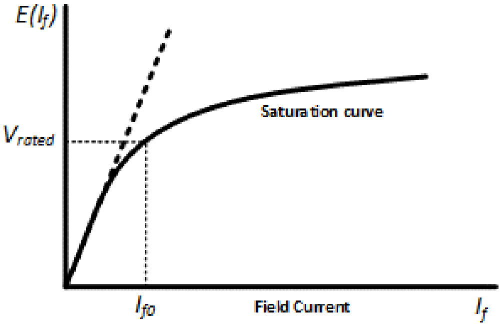

Figure A-2. Typical no-load characteristic of synchronous machine (Source: NRFL).

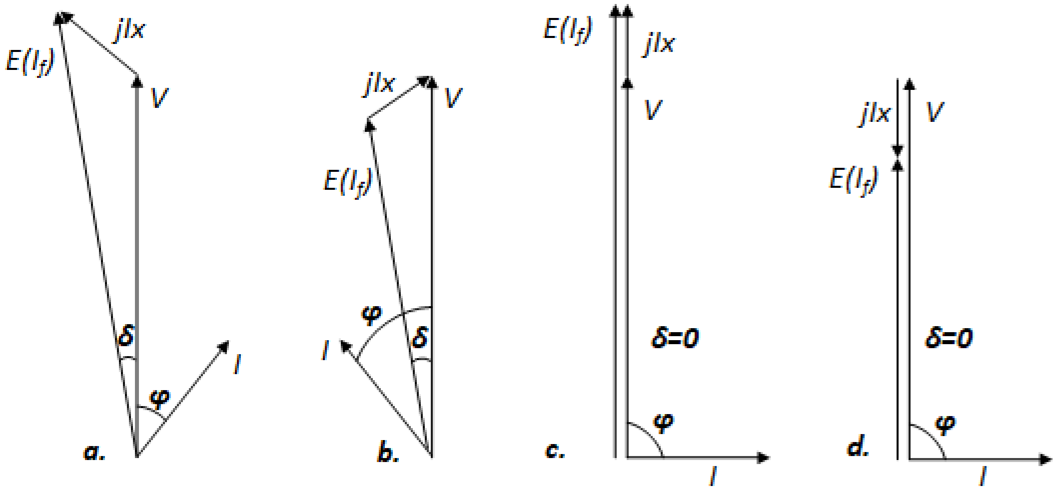

Figure A-3. Vector diagrams of a synchronous generator (a) over-excited, (b) under-excited, (c) over-excited SC mode, (d) under-excited SC mode (Source: NREL).

In under-excited mode the generator current is lagging, so it acts as an inductive load consuming reactive power. In over-excited mode the generator current is leading, so it acts as a capacitor producing reactive power.

An important thermal limitation in synchronous machines is caused by eddy current losses in the laminations of stator core due to end turn flux of armature winding. This heating imposes a limitation on the operation of synchronous machine known as end-part heating limit. Stator lamination is parallel with flux along the air gap of the machine. However, the end turn leakage flux goes through stator core almost perpendicularly as shown in Figure A-4. As a result, increased eddy current in stator end in under-excited generators my increase significantly causing severe limits in machine output.

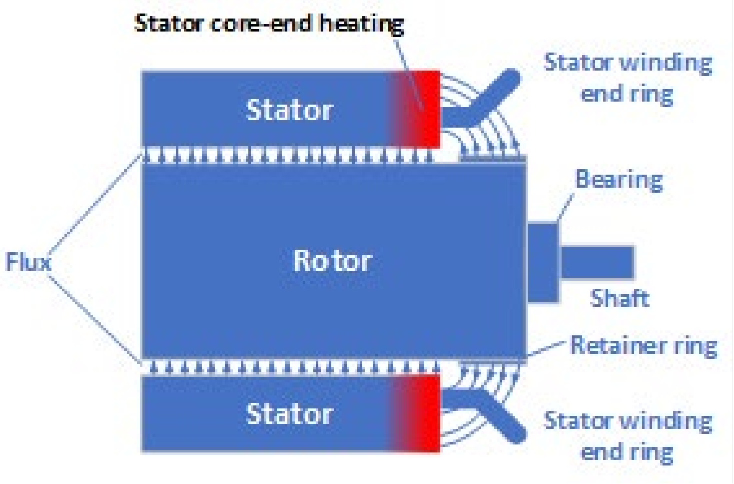

Figure A-4. Stator end-core heating in synchronous machines (Source: NREL).

All above described thermal and stability limitations must be addressed in design stage of synchronous generator based on various operational characteristics including desired steady-state, dynamic and overload performance.

Some of these limitations are indicated in a generator V-curve are shown in Figure A-5 that we calculated using parameters of a typical synchronous generator. Synchronous machine normally operates within the boundaries determined by thermal and stability borderlines as shown in Figure A-5. In SC mode, the machine operates along red trace bounded by the same limitations. The V-curve of the generator is non-symmetric resulting in less reactive capability in under-excited operation compared to over-excited.

NREL calculated the reactive capability of 2.5 MVA synchronous generator with rotating brushless exciter that is used at NREL Advanced Research on Integrated Energy Systems (ARIES) facility for testing various integrated hydro power/ battery scenarios. The reactive capability of 2.5 MVA / 2 MW machine is limited due to above mentioned constraints is shown in Figure A-6. P-Q characteristics of other types of generators may different based on generator design and type of excitation system.

Important parameters to consider when designing excitation control for hydro generator include both steady-state and transient requirements:

- Exciter rated voltage and current, field rated voltage and current
- Ceiling voltage under no-load, loaded and disturbance conditions
- Excitation system time
- Under and over excitation limiters, Volt/Hz limiter
- VAR and power factor control systems
- Power system stabilizer in grid connected mode
- Pole slipping protection

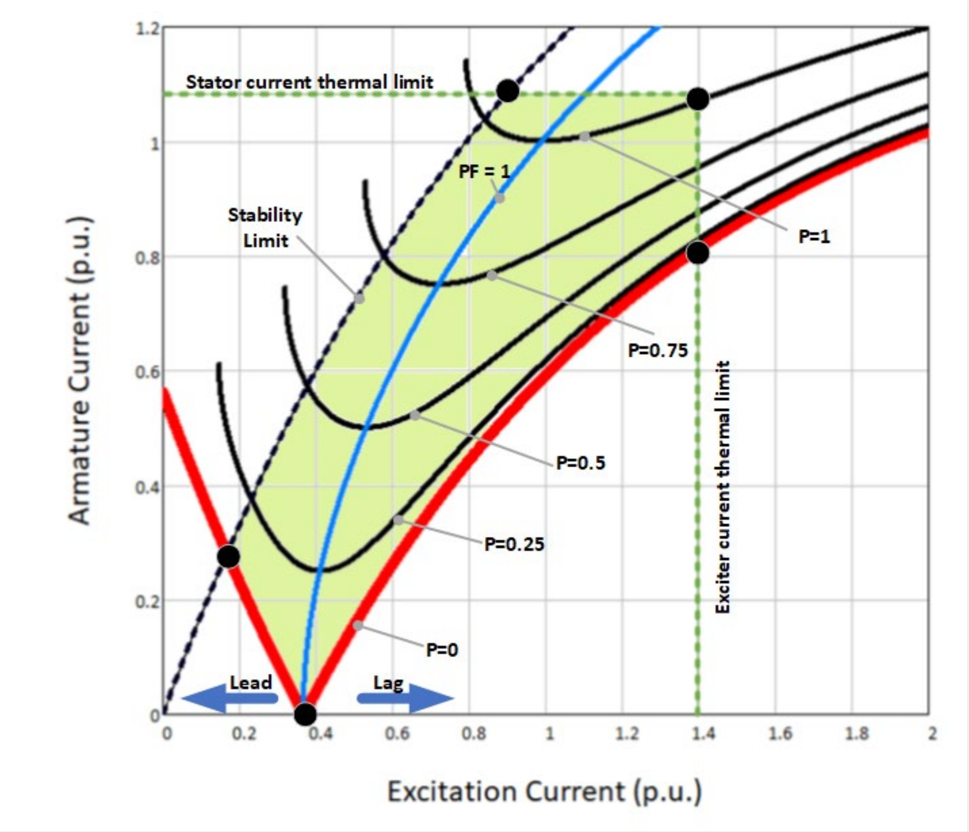

Figure A-5.Example V-curve for a synchronous machine (Source: NREL).

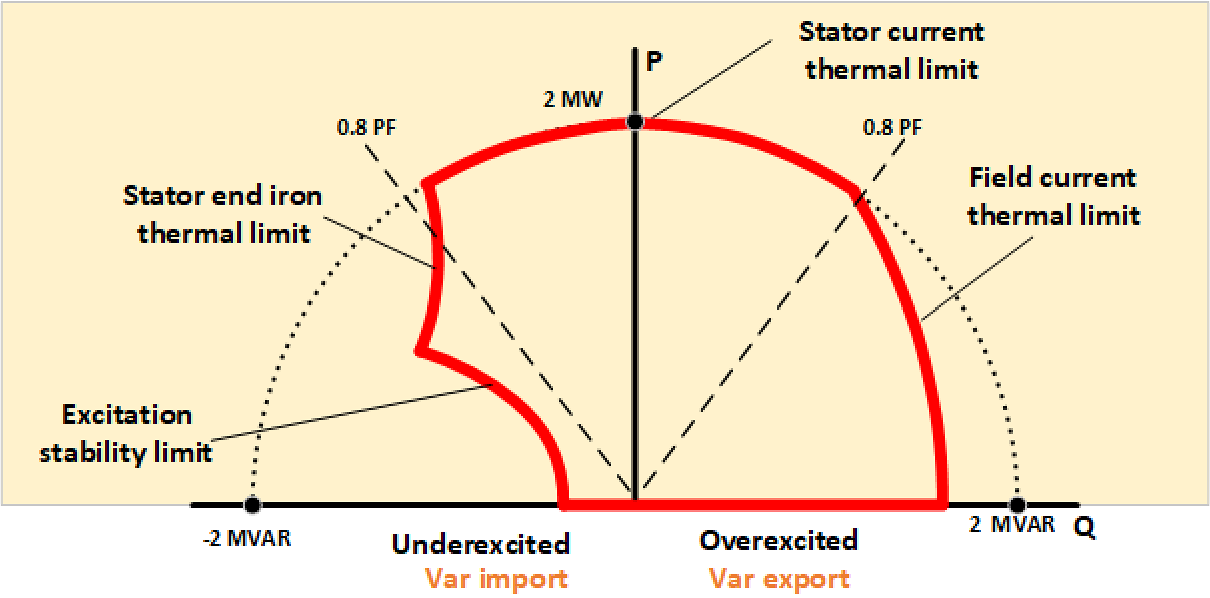

Figure A-6. Example P-Q capability of 2,5 MVA synchronous generator with rotating exciter (Source: NREL).