

Resilient Black-Start System Design and Integration With a Power Management System for an Islanded LNG Facility

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RESILIENT BLACK-START SYSTEM DESIGN AND INTEGRATION WITH A POWER MANAGEMENT SYSTEM FOR AN ISLANDED LNG FACILITY

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Abstract – This paper details the design and implementation of an automatic black-start and power management system for the essential power generation of a 1.5 GW islanded liquefied natural gas facility, addressing the critical challenges of maintaining operational reliability and stability in the absence of a steady utility connection. The system incorporates two blackout detection methods and two energization strategies, including the soft energization of essential diesel generators to mitigate transformer inrush current. The paper emphasizes resilient algorithm design, which features dynamic pause-and-resume functionalities via an intuitive human-machine interface to manage various failure cases with minimal operator intervention. Additional functionalities include priority-based load restoration, voltage and frequency control, load sharing for essential diesel generators, and load-shedding schemes. Furthermore, the paper discusses a custom island-to-island synchronization system that facilitates seamless reconnection to the main generation using existing relay infrastructure. The system was successfully commissioned and the paper highlights key lessons learned and challenges encountered during the process.

Index Terms — Black-Start System, Power Management System (PMS), Soft Energization, Load Restoration, Load Shedding, Voltage and Frequency Control, Island Synchronization, Islanded LNG Facility.

I. INTRODUCTION

Liquefied natural gas (LNG) facilities rely on a stable and reliable power supply to keep critical processes running. In islanded facilities, a loss of main generation results in a complete power blackout, quickly shutting down essential auxiliaries, making fast and dependable blackout recovery essential. During such an event, the essential power generation supplies limited power to critical auxiliary loads needed to restart the first main generation gas turbine generator (GT).

This paper presents the design and implementation of a resilient automatic black-start and power management system (PMS) for the essential power generation of a 1.5 GW islanded LNG facility. This system enables fast black-start sequencing of essential diesel generators (EDGs), maintains essential voltage and frequency stability, and supports automatic synchronization, which enables seamless island-to-island synchronization of the essential and main generation.

The EDGs serving both black-start and essential power functions are connected to a substation designated as the black-start substation and is referred to in this paper as the black-start

system. The PMS referenced in this paper refers to the essential power generation system PMS unless otherwise noted.

A. Operational Challenges in Black-Start Systems

Islanded LNG facilities face several challenges during blackout recovery that affect both system stability and the timing of restoration. Without a utility reference, when main generation is offline, system voltage and frequency must be regulated solely by the EDGs. In this condition, step changes in load can produce frequency dips and voltage excursions [1] [2].

Energizing transformers and motors during early stages of black-start further complicates blackout recovery. Large transformers draw magnetizing inrush currents, which can reach several times the rated current due to the magnetic properties of the transformer core and the influence of residual flux when de-energized. The closing angle of the applied voltage and residual flux linkage determines the resulting DC offset, causing inrush levels to vary each time a transformer is energized [3]. Techniques like point-on-wave (POW) switching can mitigate this effect when individual breaker poles are closed typically at voltage peak for an inductive circuit. However, this can vary depending on the residual flux in the transformer [4], POW switching is not an option in medium-voltage switchgear due to the inability of independent pole closing operation of medium-voltage circuit breakers, as in the example black-start substation discussed in this paper.

Protection schemes designed for normal system operation may also conflict with the requirements of EDG black-start operation. Undervoltage, underfrequency, and synchronism-check elements must be supervised or modified to permit dead-bus energization and prevent unnecessary tripping.

A bus is typically classified as dead based on its measured voltage level. For this application, a three-phase voltage below approximately 20 percent of nominal is considered indicative of a dead bus. Dead-bus breaker closing introduces its own hazards, such as a potential transformer (PT) fuse failure, which can falsely indicate a dead condition. Reference [5] discusses different factors that need to be considered for detecting dead bus conditions.

Essential power operations are also time-sensitive. EDGs must restore power to critical auxiliary systems, such as lighting, instrument air, cooling water, lube-oil pumps, and other critical systems that are required to maintain the overall facility in a safe, stable condition. Following stable return of power to essential systems, black-start sources energize equipment required to restart the first GT. Any misoperation during this process can

B. Resilient Black-Start Algorithm Design

The algorithm presented in this paper incorporates several capabilities such as:

1. Verification of true dead-bus conditions through three-phase voltage measurements and supervision of the undervoltage element with a fuse-fail monitor using microprocessor-based relays (μ PRs).
2. Controlled voltage-ramp, or soft energization, which gradually builds transformer flux and reduces transformer in-rush during a black start. (Described in Section III.)
3. Automatic corrective action when an engine fails to start, including opening breakers, reselecting units, and continuing the sequence with the next available engine.

4. Assessment of alternate breaker paths to ensure transformers, black-start buses, and EDGs can be placed on the same electrical island even when preferred paths are unavailable due to breaker malfunction or communications loss.
5. A configurable pause-and-resume mechanism that permits operator intervention without restarting the sequence.

C. Example Power System Topology for Islanded LNG Facilities

Figure 1 shows an example configuration which includes incorporation of a secondary selective main-tie-main (MTM) scheme. The normal power source, typically the primary generation of the facility (Islanded Main Generation in Figure 1), is connected to multiple load substations under normal operating conditions. The redundant backup power feeders to the load substations come from the black-start substation, which is also normally powered by the Islanded Main Generation. This design ensures backup power availability during main generation outages. The black-start buses are kept energized at all times, enabling the downstream MTM scheme to transfer loads in the event of a loss of power from the primary generation source.

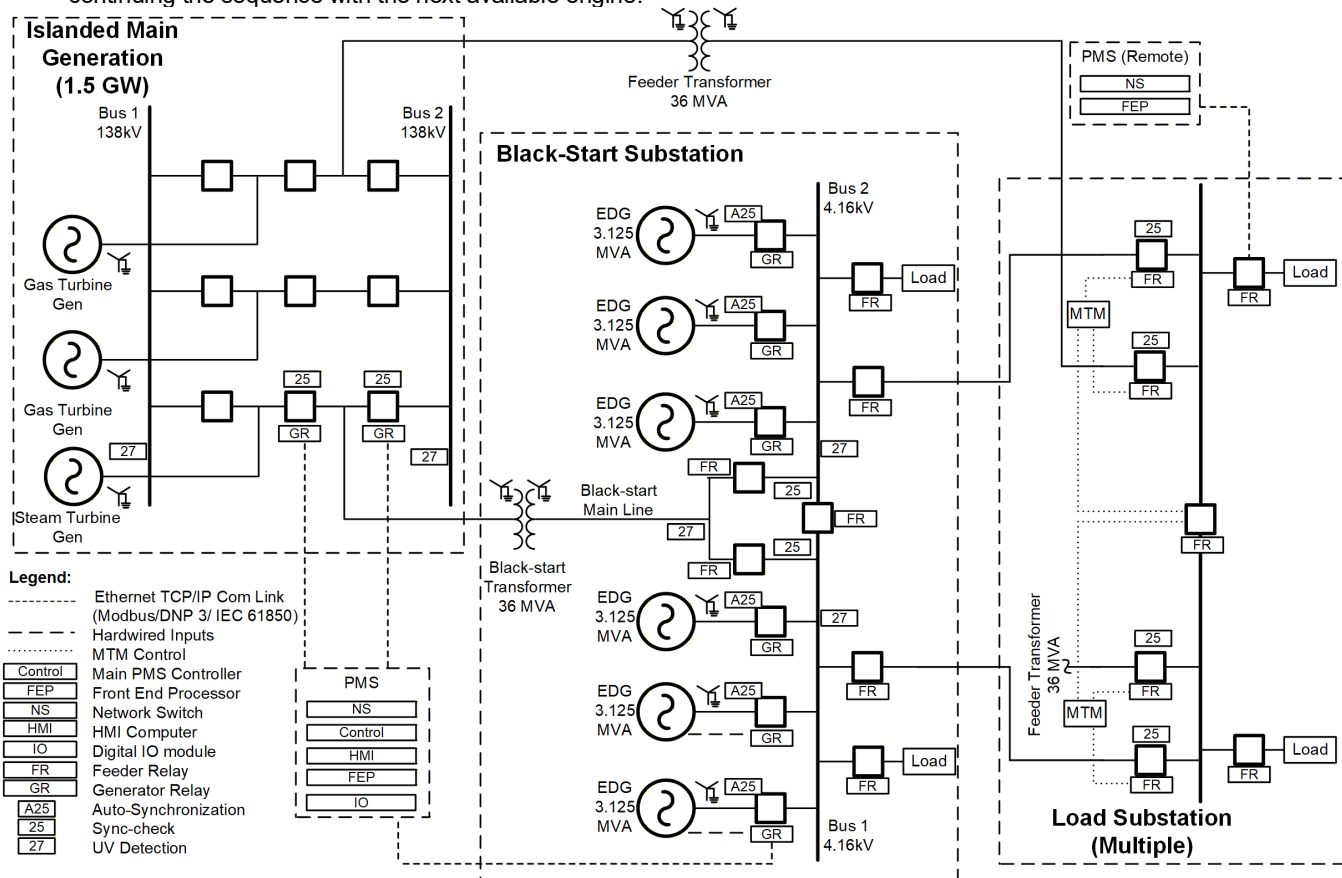


Figure 1 Example Power System Topology of an Islanded LNG Facility

D. Core PMS Functions

The PMS provides the foundational control infrastructure required for reliable black-start execution. Core PMS functions include:

1. A generation control system (GCS) which includes automatic generation control (AGC) and voltage control system (VCS). These systems regulate active and reactive power of EDGs, enabling dynamic load sharing capabilities as well as maintaining system frequency and voltage. These systems are also used to update the EDG governor and automatic voltage regulator (AVR) dispatches in a controlled manner for ramping units up or down.
2. A topology-tracking algorithm identifies electrical islands and confirms the connection between different load and source assets in real time.
3. Contingency-based load shedding (CLS) and underfrequency-based load shedding (UFLS) schemes protect against overload and frequency collapses during the restoration process.
4. An automatic synchronization system enables controlled synchronization of EDGs as well as island-to-island synchronization used for connecting back to upstream generation after the restoration process is complete. This system also uses AGC and VCS features.
5. Priority-based load restoration manages the sequencing of load additions based on operator-configured priorities, expected load magnitudes, and stability criteria.
6. Complementing PMS architecture, the black-start system leverages the PMS human-machine interface (HMI) to introduce dynamic pause-and-resume functionality, reducing operator intervention during blackout scenarios.

II. UNDERSTANDING OF PMS

A. Hardware, Software, and Communications Infrastructure

The PMS consists of redundant power system grade programmable logic controllers (PLCs), redundant operator HMIs, and a network of μ PRs, as shown in Figure 1. It executes embedded control algorithms using IEC 61131-based logic and exchanges data with field devices over both high-speed and low-speed communications protocols [6].

High-speed protocols, like IEC 61850 Generic Object-Oriented Substation Event (GOOSE), are used for breaker status; permissives, load-shed triggers; and other time-critical signals [7] [8]. These signals run within the PMS high-speed task cycle, generally in the 2–10 ms range, and support overall load-shed round-trip times of approximately 40–90 ms, depending on system architecture and network latencies. Low-speed protocols, such as DNP3.0 [9] or IEC 61850 Manufacturing Message Specification (MMS), are used for metering, analog values, and non-time-critical inputs and outputs. These are processed in slower tasks in the PLC on the order of 100–300 ms.

Breaker statuses, protection elements, metering data, and other critical signals are collected from μ PRs distributed across the system, allowing the PMS to track the accurate electrical topology in real time. The system is vendor-indifferent and supports any μ PR capable of standard industrial communication protocols. All system states, alarms, and control actions are

accessible through redundant HMIs, where operators can observe system conditions and interact with the PMS during restoration.

B. GCS

AGC and VCS algorithms are responsible for dispatching MW and MVAR set-point values to generator sets within an islanded system. They allow active and reactive power load sharing among generators connected to the same electrical island, while also regulating MW and MVAR flow across tie lines. References [10] and [11] explain AGC and VCS algorithms in detail.

AGC and VCS algorithms perform the following functions:

1. Controlling the system frequency and voltage of each island disconnected from upstream main generation in this application.
2. Controlling the MW and MVAR flow across the tie lines according to user-entered set points from the HMI.
3. Keeping the generator output within an allowable operational region of MW and MVAR based on PQ curves as well as user-entered preferred operational regions.
4. Calculating accurate governor and AVR dispatch set points under all islanding conditions as generators enter or exit service or as load changes occur.
5. Generating frequency and voltage alarms for operators when island frequency and voltage deviates from defined limits.
6. Recomputing solutions every algorithm cycle at high speed (2–10 ms range) as generator participation changes over time.
7. Dispatching for live-live (three-phase voltage above 80 percent of nominal) bus synchronization.

For coordinated control of the EDG governor and exciter, the system employs the following control method:

1. AGC dispatches active power by sending rising-edge pulses to the governor, which accumulates these pulses as a bias on the speed reference, producing step changes in engine output, as shown in Figure 2.
2. VCS dispatches reactive power using rising-edge pulses to the AVR, which similarly sums the pulse count into its voltage set point, as shown in Figure 3.

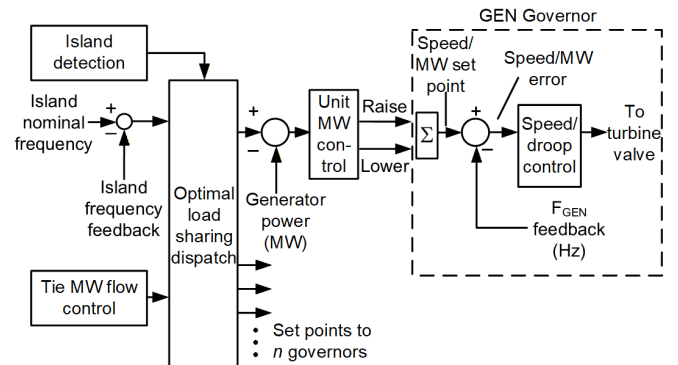


Figure 2 AGC System

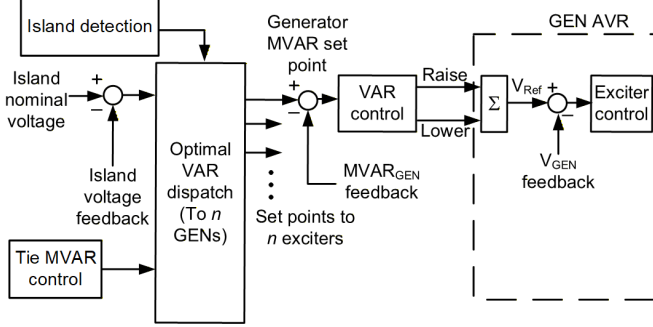


Figure 3 VCS System

The governor and AVR interfaces both use rising-edge triggered pulse trains whose accumulated count represents the commanded change. This method avoids challenges associated with set-point controls or pulse-width modulated controls during communications failures.

C. Load-Shedding System

The CLS scheme sheds load based on the predicted power deficit that occurs when a breaker opens under load and interrupts power flow. Following such a contingency event, CLS compares the remaining generation output and instantaneous reserve margin (IRM) against the total plant load and sheds sufficient load to keep the system demand within the available generation capacity, as shown in (1). This approach limits frequency decay by restoring the generation-load balance quickly. The IRM represents the additional power a source can supply while maintaining frequency within acceptable limits (typically ± 1 Hz). Various factors, like the prime mover (engines or turbines) capability, fuel-pressure control, and intercoolers, dictate the IRM of a machine [10] [11].

$$L_n = P_n - \sum_{g=1}^m \text{IRM}_g \quad (1)$$

where

- n contingency event number.
- m number of sources in the system after n event.
- g generator number, 1 through m .
- L_n amount of load selected for n event (MW).
- P_n power disparity caused by n event (MW).
- IRM_g incremental reserve margin of all sources before n event (MW).

UFLS operates in an islanded system as the engines on the island decelerate on an overload condition causing a decay in frequency. An oversized engine on the prime mover can maintain system frequency even as large additional loads are applied. As a result, the generator can be driven into a thermal overload condition without triggering UFLS. In such cases, a dedicated overload-shedding scheme is required to protect the generator from sustained thermal stress. The UFLS scheme provides backup protection by shedding load when system frequency falls below defined thresholds, where μ PRs detect underfrequency and rate-of-change-of-frequency (ROCOF) conditions locally, and these triggers determine the amount of load to shed based on predefined frequency levels and the severity of the frequency decline [10] [11]. Determining UFLS trigger set points requires performing a detailed transient stability study. These triggers are

set up on μ PRs across the system and are received by the PMS over high-speed communications protocol.

D. Topology-Tracking Algorithm

A topology-tracking algorithm identifies electrical islands by using high-speed breaker status inputs, supervising them with low-speed analogs, like MW flow across those breakers. By combining fast status changes with power-flow supervision, the system algorithmically determines which buses are electrically connected in the system.

III. BLACK-START SYSTEM

A. Blackout Detection Methods

A blackout event is the condition in which one or more facility islands simultaneously transition to a de-energized state, which is typically indicated by sustained three-phase voltages reaching near zero values for all buses on the island. In this state, no energized sources remain connected to the affected buses on the island.

The initial and most critical step in implementing a black-start scheme is the accurate detection of a blackout event. In islanded facilities, blackout detection can be based solely on the status of main generation breakers. However, this approach may introduce delays if breaker operation occurs with extended undervoltage tripping time delays. Practical experience has shown that using undervoltage element pickup and timers from multiple μ PRs distributed across the system provides a more robust method for blackout detection. When multiple μ PRs detect sustained undervoltage conditions, the PMS black-start logic evaluates these signals from different locations to determine whether a blackout has occurred. Redundant detection across multiple devices is required to prevent misoperation due to a faulty μ PR or failed PT.

As shown in the example in Figure 1, undervoltage elements (27) [12] are configured on μ PRs across the main generation bus, typically set to pick up when voltage falls below 0.2 pu. If the voltage remains below the threshold for more than five seconds, the 27 element asserts a fuse-fail supervised bit via high-speed IEC 61850 GOOSE messaging to the black-start system, which validates the blackout condition and initiates the appropriate black-start sequence.

The two primary types of blackout detection methods for power system configuration shown in Figure 1 are:

1. System-wide blackout: If μ PRs on both the Islanded Main Generation buses and the Black-Start Substation buses report undervoltage trips to the black-start system, a complete blackout is declared and a system-wide black-start sequence is initiated (see Figure 4).
2. Local area blackout: If undervoltage trips are reported only by μ PRs in the Black-Start Substation buses, a local blackout condition is declared, and the corresponding black-start sequence is initiated. This scenario may occur if the Black-Start Transformer trips or is out of service. Maintaining redundant power sources is critical for LNG facilities to ensure continuous supply to load buses and guarantee backup power availability when main generation is unavailable (see Figure 4).

A third manual detection method allows an operator-initiated black-start sequence. This capability provides operators with direct control to bring EDGs online when required, offering flexibility during commissioning, testing, or abnormal conditions where automatic triggers do not apply. It also serves as an additional safeguard, enabling proactive recovery actions to minimize downtime and maintain process safety. The overall black-start auto-detection logic can also be disabled via the PMS HMI, as shown in Figure 4.

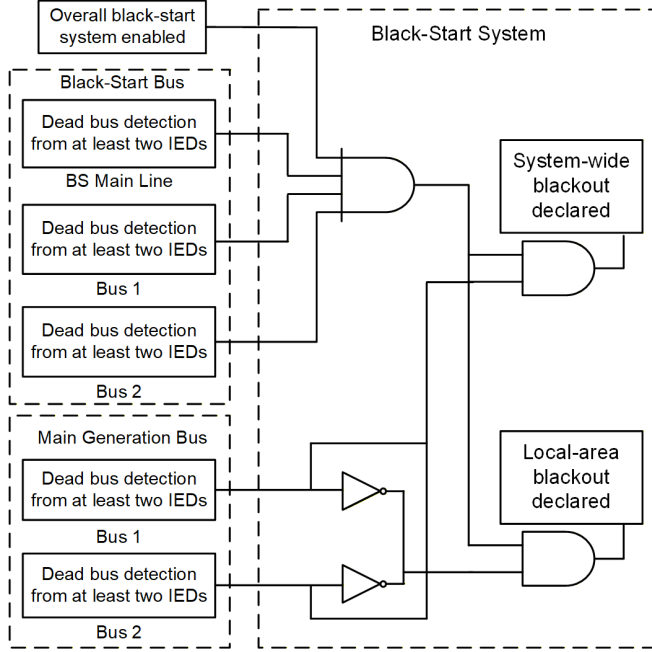


Figure 4 Blackout Scenario Detection

B. Black-Start Energization Strategies

The power system configuration for an LNG facility, as shown in Figure 1, calls for two distinct black-start energization strategies to address different operational challenges during system recovery. Each strategy follows a unique sequence of operations.

The first energization strategy focuses on mitigating inrush currents associated with energizing large transformers by employing a controlled soft energization approach. Uncontrolled transformer energization can cause inrush currents up to 10 times the transformer rating [13]. These currents can cause severe voltage dips and trip the EDGs during start up in a black-start sequence. The current magnitude varies with the magnetic properties of the transformer core and the influence of residual flux when de-energized. The magnetizing branch can be expressed as (2).

$$v_p(t) = R_1 i_m(t) + L_1 \frac{di_m(t)}{dt} + \frac{d\lambda_m(t)}{dt} \quad (2)$$

where

ϕ	magnetic flux in the core.
i_m	magnetizing current.
R_1	winding resistance.
L_1	leakage inductance.
$\lambda_m = N\phi(t)$	magnetizing flux linkage.

$$v_p(t) = V_p \sin(\omega t + \alpha) \quad \text{applied voltage waveform.}$$

α closing angle relative to the source.

Hysteresis creates remanent flux after de-energization, which sets the initial condition at closing. At the instant of energization t_0 , the breaker closes at angle α relative to the source voltage and the core carries remanent flux ϕ_r , so $\phi(t_0) = \phi_r$. If ϕ_r does not coincide with the steady-state flux trajectory implied by $v_p(t)$ and α , the required flux waveform cannot be achieved without a DC component in $i_m(t)$. This DC component biases the core toward one side of the magnetization curve. It produces asymmetric flux and drives early half-cycle saturation, which yields large inrush and strong second-harmonic content that can extend protection blocking. The DC component decays with a time constant proportional to the source and winding X/R ratio. Reference [13] shows the impact of different ramp rates on inrush.

The second strategy represents a more conventional and time-efficient method. This can be employed in scenarios where inrush mitigation is not the primary concern, but rapid restoration of critical loads is essential for process continuity.

1) Controlled Black-Start Energization Sequence

This energization sequence is used in case of a system-wide blackout for the configuration shown in Figure 1 to mitigate inrush on the black-start transformer. This approach is equally applicable to feeder transformers that require controlled energization under similar conditions. The EDGs designated for soft excitation of transformers must be configured with an appropriate voltage ramp rate, which is determined by the transformer MVA rating [13]. A dedicated study can be performed to evaluate the required ramp-rate settings based on transformer characteristics and generator capability. These ramp rates are fine-tuned and validated through field testing to achieve consistent and stable energization. The PMS VCS control loop is activated after successful soft energization is completed.

Upon detection of a blackout, the following sequence of operation is followed:

1. All breakers are tripped to isolate the black-start substation buses. All buses associated with black-start units are de-energized and cleared.
2. Specific breakers are closed to ensure the black-start units are connected on the same electrical island. In the configuration shown in Figure 1 this step would close the black-start substation tie breaker.
3. Other breakers in the system topology are closed to connect transformers to the same bus as the EDGs. This would be either one of the incomers to the black-start substation shown in Figure 1.
4. The first available EDG breaker to be used for soft energization is closed. The selection of EDGs for initial startup can be prioritized based on either accumulated run-time, to balance operating hours across units, or predefined priority settings configured in the HMI.
5. A start command is sent to the selected EDG set. Upon receiving a start command the local EDG controller starts the engine, which ramps up the rpm. Once the EDG reaches nominal frequency, the AVR kicks in and slowly ramps up the voltage to nominal, while maintaining V/F (volts per hertz) ratios.

6. Once the EDG bus is stable within healthy voltage and frequency deadband limits, the remaining EDG sets are started and healthy voltage and frequency at EDG terminals are verified.
7. Synchronized closing of remaining EDGs on the bus is initiated.
8. Once the desired number of EDGs are synchronized on the bus, priority-based load restoration begins.

For Steps 2, 3, and 4, all breaker operations involve dead-dead closing, and protection settings must be coordinated to permit these actions safely.

2) Rapid Black-Start Energization Sequence

Upon detection of a blackout, the following sequence of operation is followed:

1. All breakers are tripped to isolate the black-start substation buses. All buses associated with black-start units are de-energized and cleared.
2. Specific breakers are closed to ensure the black-start units are connected on the same electrical island. In the configuration shown in Figure 1, this step would close the black-start substation tie breaker only.
3. All available EDGs are started.
4. Live-dead closing on the dead bus of the first EDG that has terminal voltage and frequency within defined deadband limits is initiated.
5. Synchronized closing of the remaining started EDGs that have healthy terminal voltage and frequency within defined deadband limits is initiated once the bus is energized.
6. Once the desired number of EDGs are synchronized on the bus, priority-based load restoration begins.

Once EDGs are online and load restoration begins, the AGC and VCS algorithms take over to dispatch active and reactive power set points. Load sharing among EDGs is then managed automatically based on operational range configured through the HMI.

C. Priority-Based Load Restoration Algorithm

Load restoration is identical for both black-start energization strategies and begins once the black-start substation buses achieve stable voltage and frequency conditions and the desired number of EDGs are online, as configured by the operator via the HMI. Loads are restored based on predefined priorities entered through the HMI. Individual loads can be inhibited from restoration by setting a priority of zero.

An available load is one with no communications loss between the controller and load breaker μ PR, and a non-zero priority. If the load is unavailable, it is skipped from the restoration process to prevent undesired action. In addition to priority, the algorithm considers the expected MW demand for each available load, which is also configured via the HMI. Before restoring the next available load, the algorithm calculates the available generation capacity on the island for the next priority load being restored. If the expected MW of the highest-priority load to be restored exceeds the available capacity, the restoration process moves on to the next highest-priority load. The available generation

capacity is dynamically updated based on the amount of load added to the system.

The restoration process, as shown in Figure 5, proceeds by energizing the highest-priority load and then waiting for a user-configured delay timer (Timer 1, which is typically between 3 to 5 seconds) before restoring the next load. This delay ensures staggered load acceptance. Before each subsequent load is energized, the system verifies that bus voltage and frequency remain within the configured deadband. Once the highest-priority load is restored, another user-configurable timer (Timer 2, which is much longer than Timer 1) is initiated, and if voltage and frequency conditions do not recover within this time window, the restoration process is aborted.

Once a load close is attempted, it is not re-attempted in case the load breaker fails to close. Additional provision to manually restore loads is provided via the HMI, allowing operators to energize loads individually, providing flexibility during system recovery.

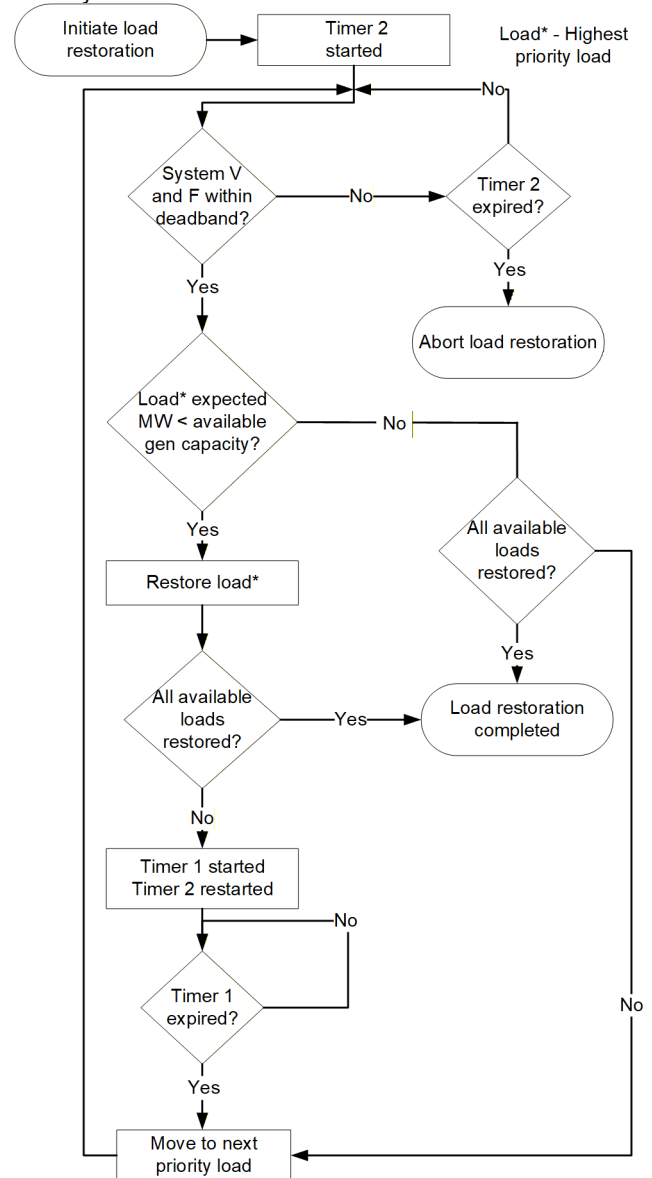


Figure 5 Load Restoration Algorithm

D. Resilient Algorithm Design

The black-start algorithm is designed with resilience for abnormal conditions during the energization sequence. This design philosophy ensures that the sequence can progress toward successful system energization by using all the resources available with minimal operator intervention.

As shown in Figure 6, the process begins in the normal operating state. Upon detection of a blackout, the system transitions into the “black-start sequence in progress” state, executing the predefined steps for energization and load restoration discussed in previous sections. If all steps are completed successfully, the state transitions to “black-start sequence completed”, and the system returns to normal operation after operator acknowledgement, re-arming the algorithm for another blackout event.

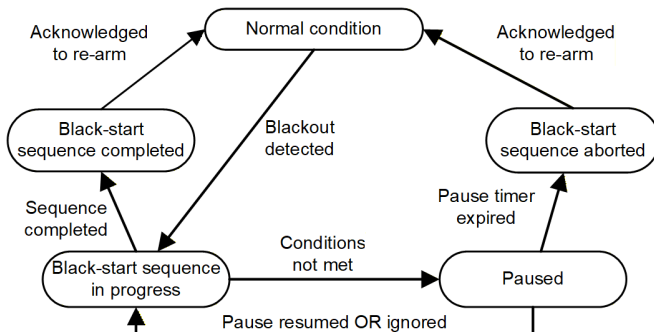


Figure 6 Black-Start System States

Figure 7 shows the control logic employed for each action in the black-start energization sequence. When an action is initiated (e.g., with a breaker open or close command), the algorithm enters a monitoring interval (Wait Time 1), during which it expects confirmation of the expected response, such as a breaker status change. If the expected response is received within this time interval, the algorithm proceeds to the next action in the sequence without delay.

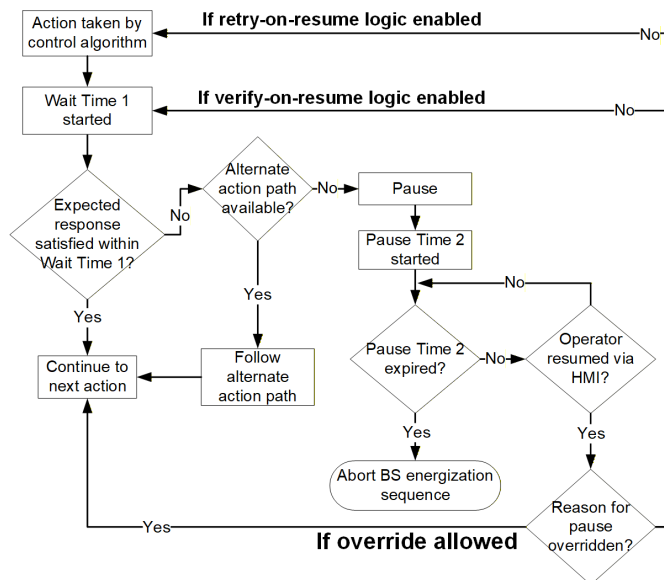


Figure 7 Black-Start Algorithm Control Flow

If any condition in the predefined energization sequence is not met and there is no alternate path available to continue the sequence, the algorithm enters a paused state for a predefined period of time (Pause Time 2 in Figure 7). If this predefined pause timer expires without any operator action to resume, the sequence is aborted. The system is then returned to a normal state after operator acknowledgement to re-arm the algorithm for another blackout event.

Once the paused state is entered, the operator has the option to resume the sequence with or without overriding the reason for pause. The configurable algorithm needs to be set up properly as overriding the abnormal condition may not be desirable depending on the scenario.

If the operator chooses to resume while overriding the reason for the pause, the algorithm ignores the abnormal condition and continues with the next step in the sequence. No further checks or retries are performed for the paused action.

If the operator chooses to resume without overriding the abnormal condition, the algorithm takes the respective control action depending on how it is configured. In case a retry-on-resume scheme is employed, the algorithm reissues the original control command (e.g., breaker close command if not already closed) upon resuming and then monitors for successful completion within the defined time window (Wait Time 1). If the condition remains unsatisfied, the algorithm re-enters the paused state. If the algorithm is set up to only verify-on-resume, it does not reattempt the control action. It assumes corrective action was taken during the pause and simply verifies whether the desired condition is now satisfied. If the condition is met, the sequence proceeds. If not, the algorithm re-enters the paused state after the defined time window (Wait Time 1).

The algorithm can be configured to employ the different schemes mentioned above for different steps in the energization sequence. For example, certain actions, such as initiating synchronization on EDG breakers, often benefit from automatic retries upon resuming because if the synchronization window times out, this scheme ensures that remaining units can be brought online with minimal operator intervention simply by resuming the sequence. Conversely, for actions where repeated attempts may be undesirable, the verify-on-resume approach is preferred, relying on operator correction during the pause.

It is important to note that the algorithm only issues a control command if the desired state is not already achieved. For example, if the sequence requires a breaker to be open and the breaker is already in the open position, no open command will be sent. Desired conditions are continuously monitored throughout the sequence to ensure actions are taken only when required.

The configurable time after an action taken by the control algorithm (Wait Time 1) is also different for each step in the energization sequence. These times are tuned during onsite commissioning depending on the expected delays in response to the control action taken.

Another key aspect of resiliency in the black-start algorithm (shown in Figure 7 as the “alternate action path available?” decision step) is the ability to exhaust all viable options or alternate paths before entering a pause state. For example, during the EDG starting step of the soft energization sequence, if the first selected unit breaker fails to close or does not achieve healthy voltage and frequency within the defined time window after a start command is issued, the algorithm automatically attempts the next available EDG before pausing. A pause state

is only entered after all available EDGs are attempted during the sequence.

Similarly, when closing specific breakers to ensure all EDGs are on the same electrical island or closing other relevant breakers to ensure that the transformer is also connected on the same electrical island before soft energization, the algorithm considers other predefined paths to achieve the same objective if the original path breakers fail to close. For example, in the configuration shown in Figure 1 during Step 2 and Step 3 (soft energizations sequence), if the tie breaker closes but the preferred main breaker fails to close, the algorithm will attempt closing the other main incomer in the MTM configuration to achieve the same objective of connecting the transformer to the same electrical island as the EDG to be used for soft energization.

To achieve the objective of ensuring all viable paths are exhausted to ensure different assets are on the same electrical island, the black-start system may use the PMS intelligent topology-tracking algorithm to dynamically evaluate alternate connectivity paths and attempt breaker operations along those paths until all possible combinations are exhausted. Such functionality is valuable in more complex power system topologies where multiple redundant paths exist. Due to its complexity and specialized application, a detailed discussion of this algorithm is beyond the scope of this paper.

It should be noted that following an alternate path may also call for a corrective action to undo the previous action taken in the algorithm to move forward. In such cases, the next action, shown in Figure 7, becomes the corrective action. An example of such a case is shown in the first EDG start up sequence in Figure 8 for soft energization. The sequence shown employs verify-on-resume logic without the option for an operator to override the abnormal condition. Additionally, the two sequential steps of Actions 1 and 2 in Figure 8 include alternate action paths, which essentially are the number of other available EDGs in the black-start system. The pause is only entered once the algorithm has attempted to bring all available EDGs online. Action 2 requires a corrective action as shown, which is tripping the EDG breaker before attempting the next EDG closing. Action 4 continues to start the remaining EDGs once one EDG is brought online. The next steps would then be to synchronize all remaining EDGs on the bus and then begin staggered load restoration.

IV. INTEGRATED SYNCHRONIZATION SYSTEM

The synchronization system is designed to match the voltage, frequency, and phase angle of isolated power islands or EDGs to predefined thresholds, enabling circuit breakers to close safely at matching phase angles.

In this application, synchronization is required under three scenarios:

1. Black-start condition: Synchronization of all EDGs to one another if black start triggers.
2. Switch to normal operation: Synchronization of EDGs back to the main power generation.
3. Manual EDG start/stop and synchronizing to bus for periodic testing and exercising.

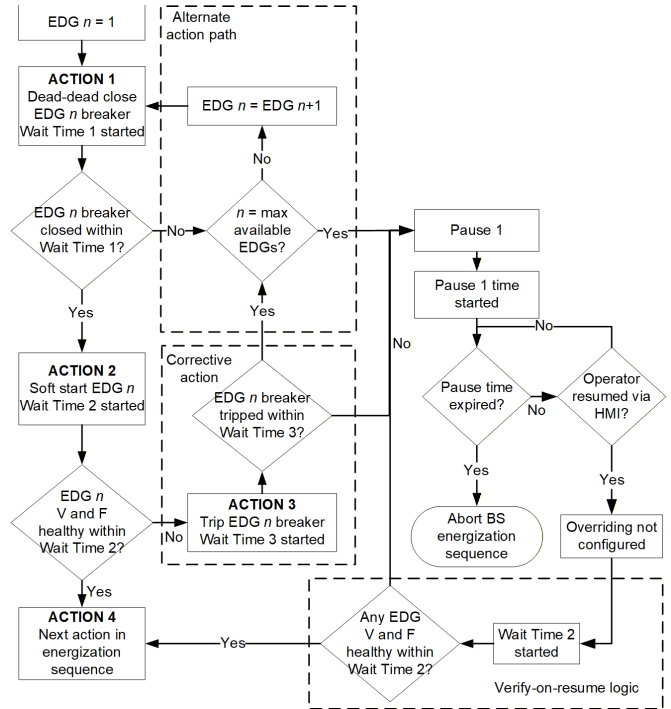


Figure 8 First EDG Soft Energization Sequence

Modern day μ PRs include both the 25 (synchronism check) and A25 (advanced synchronization) elements [14], enabling the μ PR to perform two key functions: first, bringing the generator speed and voltage close to the reference bus, and second, verifying that synchronism conditions are satisfied before closing the breaker. When enabled, the 25 element continuously monitors generator voltage, frequency, and phase angle relative to the reference voltage. It asserts a logical 1 when all defined synchronism conditions are met.

Automatic synchronizer systems eliminate the need for traditional synchroscope hardware and manual breaker operations, delivering precision and automation in generator synchronization. By leveraging governor and exciter control through hardwired speed and voltage correction set points, the A25 system achieves seamless synchronization of EDGs during black start. The designated points, labelled A25 in Figure 1, show where auto-synchronization of EDGs can be performed.

Following a blackout event, one EDG is first energized and closed onto a dead black-start bus to establish a reference point. Subsequent backup EDGs synchronize to this reference using the local μ PR once the synchronization command is received.

For synchronizing local EDGs, A25 is used by local μ PRs to synchronize EDGs to the live black-start bus. Figure 9 shows the hardwired and software connections required for local EDG synchronization.

Seamless synchronization back to the main generation is critical for operational reliability. For island-to-island synchronization, the local μ PR uses only the 25 element for such cases. When synchronization is initiated from the relay, a command is sent to the black-start system to synchronize all EDGs with the main generation. The PMS, using an internal sync algorithm, adjusts the EDGs to match the reference voltage. Once all synchronism conditions defined for the 25 element are satisfied, the local μ PR closes the breaker.

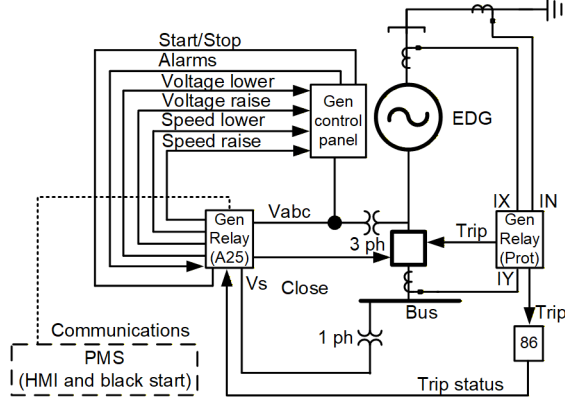


Figure 9 Synchronization Control and Communication Interface for EDG

For adjusting the 25 element on EDG [15]:

1. Voltage window low and high was set to 0.9 and 1.1 pu.
2. Target closing angle was set to 0 degree with ± 10 degrees as allowable band.
3. Max voltage difference was set to 3 percent with generator voltage higher than bus voltage.
4. Allowed slip was set to 0.06 Hz.

For adjusting the 25 element on island-to-island sync locations:

1. Voltage window low and high were set to 0.9 and 1.1 pu.
2. Target closing angle was set to 0 degree with ± 10 degrees as allowable band.
3. Maximum voltage difference was set to 3 percent.
4. Allowed slip was set to 0.1 Hz.

V. COMMISSIONING EXPERIENCE: CHALLENGES AND LESSON LEARNED

Commissioning the black-start system in the field presented challenges due to operational constraints and the lack of redundant paths, which often left some of the black-start substation buses inaccessible for testing. This made it difficult to execute the full energization sequence under ideal conditions. A major takeaway was the value of modular control system design, which enabled partial restoration and allowed commissioning to proceed despite site-specific limitations.

Commissioning synchronization settings in EDG relays also required close attention. Variations in governor and exciter response among identical units led to differences in synchronization behavior, making theoretical settings insufficient. This demonstrated that onsite fine tuning and validation of A25 parameters is essential for achieving fast and reliable synchronization during black-start operations.

AGC and VCS pulse-based dispatch from the PMS to EDG μ PRs required tuning to maintain stable voltage and frequency when EDGs operated in parallel without load. This tuning prevented EDG hunting and ensured stable control before load restoration, highlighting the need for detailed testing and calibration of AGC and VCS parameters to ensure reliable black-start performance.

During commissioning of the complete black-start sequence, nuisance tripping during EDG energization was observed. Reverse power and out-of-step were the main elements that were tripping the EDGs. This underscored that thorough end-to-end onsite testing under realistic conditions is required to validate protection coordination with the control scheme to ensure dependable operation during actual black-start events.

VI. CONCLUSION

The implementation of an automated black-start system integrated with a PMS significantly enhances the resilience and reliability of islanded LNG facilities for blackout recovery. By leveraging advanced algorithms for blackout detection, controlled energization, synchronization, and priority-based load restoration, the system ensures rapid and stable restoration of power under highly dynamic conditions. Key design features, such as soft energization, resilient algorithms, and intelligent topology tracking, mitigate operational risks, while hardware-in-the-loop testing and thorough onsite validation address commissioning challenges.

The successful deployment of this architecture demonstrated its capability to minimize downtime, safeguard critical processes, and deliver substantial operational and economic benefits, establishing a robust framework for black-start applications in complex industrial power systems.

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IX. VITAE

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