Guide to Restoration

Marketplace Training

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1. Introduction

Purpose

Blackouts have a significant impact on our economy and public health and safety. We manage the risk of these rare events by planning and practising our collective response. Although we're all familiar with our individual roles, an overview of the whole process will highlight the decision-making process and dependencies that shape a restoration.

This document walks you through a system restoration. We'll use a generic power system and apply the principles from the Ontario Power System Restoration Plan (' the restoration plan'). We'll consider the operational roles of the IESO and participants as they work together. At the end of it, you should have a very good idea of the expectations, actions and rationale that drive a restoration.

Restoration – Enablers

Successful restoration depends on three factors – coordination and direction provided by the IESO (us), timely, predefined independent actions by the participants (you), and effective communications among all involved. We'll cover the first two factors in this guide. Normal and emergency communications are covered in a separate participant-specific set of recorded presentations available on the marketplace training web pages.

What do we know about blackouts?

As we saw in 2003, it was a matter of minutes between our first indication that something bad was happening until the lights went out. Although the blackout had its roots in conditions that started to develop hours before, when the system collapsed, it happened quickly. This was true in each of the three blackouts we have experienced. The other thing we know is that every disturbance is unique to the conditions of the day and the initiating cause – so we can't predict exactly how the power system will respond or the extent of any blackout.

The restoration plan

The restoration plan recognizes the principle that every disturbance is different. It provides priorities, a path-based strategy, and prescribed independent actions for participants, while retaining the flexibility to meet the unique circumstances of any blackout. Also, it works in conjunction with existing emergency procedures, which ensures a consistent response to abnormal events.

Overview

We'll use the generic power system shown in Figure 1 to walk through a restoration scenario. The vertical black bars are transmission substations (A-I) and the lines between them are the transmission circuits. Each line represents two circuits sharing the same tower. Generating stations (nuclear, gas, wind, and hydroelectric) and loads (wholesale customers and local distribution companies) are tapped off the transmission circuits. Also, our grid is interconnected with another jurisdiction outside Ontario at Station E. Assume that hydroelectric generator G6 is under contract to provide blackstart service, which means that it can start without grid power and can energize transmission to start the restoration.

2. The Disturbance

What happens to the grid?

Assume that just prior to the disturbance, all equipment is in service and the system is safely within operating limits. The nuclear generator G1 is at full load, the hydroelectric generators are shutdown, and the gas units are partially loaded.

Let's assume that a major disturbance begins in another jurisdiction and propagates into Ontario, which then collapses the area in grey and our immediate interconnected neighbour (Refer to Figure 2). Circuit breakers at Stations D and I have opened, creating a small island of load and generation. Generator G1 is disconnected from the grid, but is operating at partial load supplying their own station service. G2 and G5 have tripped out of service. All of the remaining circuit breakers in the blacked-out area remain closed.

In the surviving island, frequency and voltage are oscillating, and power flows are very different than they were before the disturbance. Depending on the severity of the swings, automatic underfrequency load shedding and generator tripping may take place as the island tries to find a load-generation equilibrium.

What's the immediate response at blacked-out participant sites?

Although it's readily obvious that you have no power, it may be difficult for you to tell if the problem is local or widespread. When a transmission line trips out of service due to a fault, the associated circuit breakers are opened. However, in a blackout, the circuit breakers that tie you to the grid are likely to still be closed, despite the lack of potential at your site.

If you are a distributor with several step-down transformer stations, a loss of potential to all of the stations under your control is also an indication of a widespread blackout.

Your confirmation of the scope of the problem will likely come when you try to contact our control room operators. As we'll discuss later, following a significant disturbance our operators must prioritize who they speak with. In the early stages of restoration, particularly wholesale customers and distributors are unlikely to have much direct contact with us. Our phone system will ask you to elevate your call in the queue only if you have information directly related to the cause.

Your immediate response to the blackout is to:

- Implement your prescribed independent actions, which we'll review a little later in the guide
- Take whatever steps are set out in your emergency preparedness plan to mitigate the impact on public health and safety

- Invoke your crisis/emergency management processes to help you manage the emergency

What's the immediate response at the IESO?

Our operators' first task is to assess the state of the grid – what's blacked out, what's not, what's the status of the generators? How much time do we have to re-establish potential and reload generation before it becomes unavailable? Are we interconnected? Are there any islands? Although our telemetry tells us the status of the system, our first conversations are with the transmitters, our interconnected neighbours, and the large generators to confirm what we're seeing and to determine the extent of the blackout. Then we can decide the overall approach, allocate our staff and begin the restoration.

For a widespread blackout, we'll issue a System Status Report, which indicates that we are:

- Operating in an emergency state
- Suspending the market
- Implementing the Ontario Power System Restoration Plan (OPSRP)

Strategy

The challenge during any large-scale disturbance is prioritization. This applies to us and to you – particularly if you are a transmitter that controls a lot of equipment. We have to ensure that what we choose to do first is achievable with the limited number of available real-time operating staff, especially just after the incident.

Once we've determined the extent of the disturbance and the status of the system, the strategy is to:

- Stabilize the surviving island
- Begin the restoration, i.e., create an island or several islands, depending on the size of the blacked-out area. This involves recovering generation, energizing transmission, and restoring load according to certain priorities, which we'll expand upon shortly.
- Synchronize the islands to form a larger more stable system. Ultimately, we'll want to synchronize to our neighbours and the Eastern Interconnection.

Very early on, we'll share our specific restoration strategy with the transmitters, including the sources of potential we intend to use, restoration paths, number of paths to be simultaneously restored, and any other priorities. This helps the transmitters:

- Prioritize off-potential circuit breaker opening
- Assign staff to assist us
- Address the need to send staff to remote locations

3. The Island

Let's consider our island, which consists of three generators (wind, hydroelectric, and gas), a wholesale customer and a distributor.

Immediate, automatic response

Immediately following the islanding event, automatic underfrequency load shedding and generator tripping may occur as the island reacts to the transient voltages, frequency and power flows caused by the separation. Islands with small amounts of generation and load have less inertia. Typically, such islands experience larger frequency swings, are harder to control, and are more likely to collapse from a subsequent generation loss.

Also, many of today's loads are frequency and voltage sensitive and may be lost without the action of any automatic underfrequency load shedding. The challenge with frequency/voltage sensitive load loss is that it will come back on the system once parameters are within the normal range. This uncoordinated load restoration can increase the risk of island collapse.

Assume that prior to the separation, the islanded area was being supplied from the blacked out area. The island is now deficient, so G7's governor responds to try to arrest the frequency decline, but frequency continues to fall. Some loads fed from LDC3 trip due to automatic underfrequency load shedding until equilibrium is reached. This leaves the remaining island load supplied from G3 and G7. Although it may stabilize at this new generation/load balance, there is further risk to the island if the wind conditions at G3 are not constant. Changes in G3's output will cause frequency swings and may trigger further load shedding.

Independent Actions

Facility operators in the island will take independent emergency actions to respond to the abnormal frequency. Let's review the abnormal frequency response for transmitters and generators.

Transmitter

There is a deadband around the normal frequency of 60 Hz, where no independent action is required. As frequency continues to fall, load connected to underfrequency load shedding relays trips in two blocks (12% and 23%). In parallel, transmitters manually shed 25% of the connected load. If frequency continues to fall, they'll shed as much of the remaining load as necessary to return the island to 60 Hz. In our scenario, manual load shedding isn't required as the frequency recovers due to the first block of automatic underfrequency load shedding. It is important that none of the load shed by underfrequency load shedding is restored without our approval – uncoordinated load restoration could collapse the island.

Generators

In instances of low frequency, hydroelectric generators start shutdown units to secure station service and switch condensing units to speed-no-load. If the island is stable, any available hydroelectric generators are started and synchronized. Surviving units are stabilized to prevent tripping, equipment damage, or safety impact.

In our scenario, the hydroelectric generator operator starts G4 to secure their station service. G7's operators stabilize the unit and await our direction.

IESO-Directed Actions

Recall that the first element in our post-disturbance strategy is to stabilize any surviving islands. We'll be in conversation with the affected transmitters and generators in the island immediately after the disturbance. The low frequency actions we just reviewed would happen in parallel. We may collapse the island if it cannot be controlled or monitored, rather than continue to expose participant equipment to damaging conditions.

Let's assume that our island stabilizes. We will direct G7 to reload and the transmitter to pickup an equivalent amount of shed load in coordinated steps.

The generation/load balance must be carefully managed in a small island, which is much more susceptible to transients or collapse. We may direct the wind generator to shutdown or stay off-line if its output varies too much. Also, shed load that is part of underfrequency load shedding relays is always re-supplied first to enhance the survivability of the island for a subsequent generation loss. We will, in consultation with the generators, determine which unit will perform the frequency regulation role for the island. In this case, it is likely to be the hydroelectric generator G4, which is better suited to the potentially rapid output changes of a frequency control role.

4. The Blacked-out Area

What is the objective of the restoration plan?

Following a blackout, our objective is to regain a reliable integrated power system by restoring the grid (to the degree possible) using the available equipment. In doing so, we must ensure that voltage, frequency, and power flows are controlled so that we do not damage customer or power system equipment or re-collapse the grid.

Normally, generation and transmission are a means to an end; they serve load. However, in the early stages of a restoration, these roles are reversed. In the process of rebuilding the transmission skeleton and trying to stabilize and reload generation – load has an important, but clearly supporting, function.

Consider a house – it exists to provide safe, secure shelter for people. If the house collapses, your first objective is not to get the people back inside – although ultimately that's your goal. Instead, you carefully rebuild the house, recognizing that it remains vulnerable to re-collapse until it is fully built. You'll need some of the people to help you during construction, but it's not until it's all back together that you can safely admit everyone and life returns to normal. So it is with load during a restoration.

The Role of Loads

In the context of a restoration, loads fall into three categories: critical power system loads, priority customer loads, and non-designated loads (the rest).

Critical Power System Loads

Critical power system loads are direct enablers of restoration, without them we cannot restore the system. They include telecommunications, protective relaying, and monitoring and control systems. These critical components run off battery supply immediately following a blackout, but their long-term continued operation requires power from the grid.

Priority Customer Loads

Some customer loads are especially important to supply in normal conditions and should be re-supplied as soon as practical after a blackout. The interruption of priority customer loads can have undesirable impacts on health and safety and the environment. These loads are identified ahead of time by the LDC or wholesale customer in consultation with their transmitter. Priority customer loads are excluded from rotational load shedding schemes and are re-supplied ahead of any non-designated load

Typically, about 15% of a distributor's load is available for priority customer loads and critical power system loads, with the rest available for rotational or automatic underfrequency load shedding.

As described in your Emergency Preparedness Plan, you must have a plan to mitigate the effects of an extended electricity service disruption on public health and safety. Even if you are designated as priority customer load, you must still meet this obligation.

Restoring Loads

Although we ultimately want to get back to normal and restore all Ontario load, the early stages of restoration are focussed on restoring the transmission system and recovering generation. Load is only re-supplied for three reasons in the early stages of restoration.

- Critical power system loads - Loads essential to perform restoration.
- Voltage control - Unloaded or lightly loaded transmission lines act like capacitors and increase voltage on the system. As we energize transmission, we often need load to help us keep voltage within limits.
- Reloading generators - Surviving large thermal generators (fossil and nuclear) need to be reloaded as soon as possible after the disturbance, otherwise the thermal stresses and other physical limitations can slow or prevent them recovering. So after we have built a transmission path to these generators we need to reload them as quickly as possible, typically using fairly large blocks of load.

Critical power system loads are re-supplied first as we energize transmission along a path. Once these are taken care of, other load can be used to provide voltage control or to allow generators to reload.

When do priority customer loads get restored?

What if a priority customer load is not needed for voltage control or isn't directly on a restoration path? The urgency in restoring a priority customer load depends on the specific circumstances of the interruption, such as how long it has been off, the consequence of it remaining unsupplied, and how effective the mitigation efforts have been. Restoring these priority customer loads can occur only if it does not significantly delay:

- Achieving the restoration plan objectives or priorities
- Restoring critical power system loads
- Restoring transmission along a restoration path
- Reconnecting major generating stations

Restoration – Priorities

Our priorities during restoration align with the post-disturbance strategy and load restoration topics we have already discussed.

Priorities:

1. Restore grid-supplied power to all nuclear sites – to secure the generators and make them available to assist in restoration as soon as possible
2. Restore grid-supplied power to critical power system loads at transmission and generating stations – to supply station service to allow restoration to proceed
3. Restore grid-supplied power to critical power system loads fed from LDCs – to supply telecommunications within their distribution systems needed to facilitate restoration
4. Restore loads needed to control voltage and reload generation
5. Synchronize islands to each other and the broader interconnection

Where should we start?

Before we can begin restoring the blacked-out area, we need to decide where we're coming from (our source of potential) and where we're going (which transmission circuits to restore first). We have several choices for a starting point. We can use:

- Our interconnected neighbour, provided they agree. (In our scenario, we're assuming they are also blacked out and will not be able to help.)
- Another generator that survived the initial disturbance, such as G1.
- The surviving island, once it is stabilized.
- The blackstart generator G6.

The source of choice depends on the system conditions. We want to use as strong a connection as possible to restart our system. As mentioned in the island section, more inertia means a better shock absorber and better ability to manage voltage.

Let's assume that G1 is still busy stabilizing their unit, our island's frequency is too variable, and our neighbours are blacked out too. That leaves us with our blackstart generator G6, who will have started their blackstart procedures as soon as they recognized the situation. It is important to note that even if we use another source of potential to begin the restoration, we would let G6 complete their start up procedures. This gives us some flexibility should our original plan not work out.

Our first priority is to restore grid power to nuclear sites, so our initial path will be from G6 to B then on to the nuclear station at A.

Refer to Figure 3. On the double-circuit transmission lines between stations F and B we have a wholesale customer WC1 and a local distribution company LDC1. WC1 is a priority customer load, but LDC1 does not serve any priority customer loads.

Independent Actions

Let's look at what's going on at each participant's facilities.

Transmitter

The transmitter must eventually open all off-potential breakers under their control. With a limited number of staff and tools, they have to prioritize this huge task. They must also consider any limitations on the air systems at their substations, which could affect their ability to perform multiple breaker openings. They start with the stations closest to blackstart facilities and any other sources of potential they are aware of. Before even discussing restoration strategy with us, they know G6 is the blackstart generator and that the priority is to restore power to the nuclear generator G1, so they independently begin opening the off-potential breakers along that path. If they have the resources, they will also open breakers at Stations D and I, adjacent to the island.

Generators

Generators independently open all off-potential unit and switchyard breakers under their direct operational control. G6 begins blackstart procedures and, at the same time, tries to contact us to determine the extent of the blackout. If the blackout was localized, we might suspend the blackstart procedures and use another part of the grid to restore. In this case, the blackout is widespread and we let blackstart proceed to the point the generator is ready to energize the off-potential circuit from G6 to Station B, under our direction.

The other generators secure their station service with any available units in accordance with their local instructions. In this case G1 survived the disturbance and is disconnected from the grid, but is supplying its own station service. G2 and G5 have tripped out of service and will have to wait until power is restored to their switchyard before they can restart and assist in the restoration.

Wholesale Customers

Wholesale customers independently open their off-potential breakers:

- Transformer secondary breakers at step-down transformer stations that are directly connected to the grid
- Associated feeder and bus tie breakers
- Any capacitor, reactor and synchronous condenser breakers

In addition to managing the impact of the blackout on their processes, they should have a plan for load restoration. At some point we will be able to let them start restoring all or some of their load. In preparation, they must know:

- Which loads, including the expected MWs, they want to restore first, assuming everything cannot be picked up at once
- How their process affects the blocks of load they can pick up – is it in 4 blocks of 10 MW or is it one block of 40 MW?
- How their capability and load profile changes over the time they have no potential. For example, certain processes may be unavailable after 4 hours without power

Local Distribution Companies

Distributors should independently open certain off-potential breakers, which include:

- Transformer secondary breakers at step-down transformer stations that are directly connected to the grid
- Any capacitor, reactor and synchronous condenser breakers

Distributors should not open their feeder breakers or breakers further downstream in their systems, unless they need to control cold load pickup once potential is restored. As restoration progresses, more generation becomes available and we need to quickly restore large blocks of load to ensure the generators remain available to continue the restoration. To avoid delays in restoring larger blocks of load, it is faster to close the secondary breakers at step-down stations rather than wait while many feeder breakers or breakers further within the distribution system are closed.

Cold load pickup: an all season phenomenon

At any given moment in a distribution system, certain loads such as furnace motors, refrigerators, and air conditioners are not normally all operating at the same time. Following a prolonged outage, the thermostats that control these devices will all call for them to run as soon as power is restored. This can overload the feeders or cause voltage control problems.

Distributors should also prepare to restore load, which means knowing:

- Which loads, including expected MWs, they want to restore first, assuming everything cannot be picked up at once
- The blocks of load they expect to pick up, allowing for cold load effect, which becomes more pronounced the longer they are without power

Directed Restoration

We've considered each of the participants' independent actions. Now let's take a closer look at the next phase – directed restoration.

You'll recall that our first priority is restoring potential to the nuclear generator G1. The blackstart generator G6 is now ready to energize circuit F2B and begin creating a new island. We'll conference together the transmitter, G6, LDC1 and WC1, verify that all the off-potential breakers are open on our path, discuss any operational concerns, and then direct the circuit energization.

The unloaded transmission line acts like a large capacitor and will try to drive the voltage up, particularly at the open ends of the circuit at Stations F and B. We have several options to help control the voltage. We can rely on G6's voltage regulator or we could direct the transmitter to complete switching so that the critical station service loads at the substations are picked up as the line is energized. Also, we could direct the distributor or wholesale customer to add a small block of load once they have potential. As they are a priority customer load, we'll allow WC1 to restore some load as soon as it is practical.

Now that circuit F2B is on potential, we can repeat the process to energize one of the circuits from B to A and restore grid supply to our nuclear station. We'll need more load to help control voltage and to reload G1. We'll coordinate the load pick-up at LDC1 and WC1 to match G1's loading rate to ensure our new island's frequency and voltage are kept within limits. Because our new island is not very robust, we must be very methodical when we make changes to load or generation. We'll add load in small steps and allow the generators time to stabilize in between.

We've successfully completed our first objective - now what? We need to get potential back to the gas-fired units G2 and G5 to supply their critical loads and to reload them before they become limited by thermal stresses or other process constraints. We also want tie-in to our surviving island and, if we can manage it without delaying these first two goals, re-supply the priority customer load WC2. Let's assume there is sufficient staff to attempt both.

G5 can be reached by energizing their dedicated circuit, which is connected to substation F. Our preferred path to meet the rest of our goals is from B to C to D. We would already have discussed this strategy with the transmitter so they could prioritize their opening of off-potential breakers. Similarly, we would have asked G5 and G7 how long it will take for them to be ready to synchronize after we restore potential, their expected loading rate, and their maximum output.

Throughout the restoration, we may assign specific tasks to the transmitter, such as energizing and paralleling companion circuits on the paths we've already energized. This gives us some redundancy and strengthens our emerging island.

Energizing one of the circuits from F to E follows the same principle as our initial circuit restoration, i.e., get everyone on the call, verify breaker positions, discuss any operational concerns, direct coincident load restoration as needed to manage the voltage, then energize to restore potential to G5. Once G5 has potential, we'll direct them to synchronize and load, subject to any loading rate or output restrictions they may have. As they increase output, we'll direct LDC1 and WC1 to restore their load in steps.

If they haven't got enough load to meet our needs, we'll reduce G6's output to maximize the loading on G5, while maintaining the frequency in the island.

Meanwhile, we'll take the same steps on the path from B to C and on to D. Critical loads at each substation are re-supplied as we go. The load at WC2 helps to control voltage and allows G2 and the rest of the generation in our island to reload.

The next step is to synchronize our two islands at substation D. We must ensure that frequency and voltage are matched and controlled within very tight bands in each of the islands before attempting the synchronization, or we risk collapsing the whole grid.

Assume we successfully synchronize the islands. Now we have reached almost all the load and our transmission system is significantly rebuilt. We'll energize along the path from I to H and on to G, which allows us to restore at least some of the load at WC3 and LDC2. After that it is a matter of completing the loop from G to F and tying substations C and H together.

Let's assume that our gas plants and the nuclear plant cannot return to full load, and our interconnection is still unavailable, so there isn't enough energy to serve all the load. We'll direct the transmitter and distributors to start rotational load shedding. Rotational load shedding 'shares the pain' and helps to mitigate the impact on public health and safety. This lasts until the interconnection is available or the de-rated units can deliver full output.

5. Summary

In just a few minutes, we've successfully restored our simplified power system. In real life, these steps take hours. Part of the reason is the sheer scale of the job and the unique challenges that arise in each event. Another consideration is the importance of doing it right the first time. In normal conditions, the strongly interconnected Ontario grid is extremely resilient. When we start a restoration, the skeletal beginnings of our system are at risk, even from contingencies that would normally not cause a problem. A re-collapse takes us back to the first step, further delaying our efforts to get back to normal. Also, equipment is more likely to fail or have performance problems after a second disturbance. Consequently, we must continually balance our desire for speed against the need for controlled restoration, where direction is clearly understood and impact is carefully assessed.

During a restoration, you can help minimize our vulnerability by:

- Understanding your role and how it fits in the big picture
- Taking your predefined independent actions
- Responding to our direction
- Communicating effectively

Before a restoration, you can help us prepare by:

- Ensuring your operational staff are trained in their restoration duties
- Practising these duties, both in-house and through our workshops and exercises
- Ensuring your emergency plans and restoration attachments are up-to-date

6. Figures

Figure 1: Generic Power System

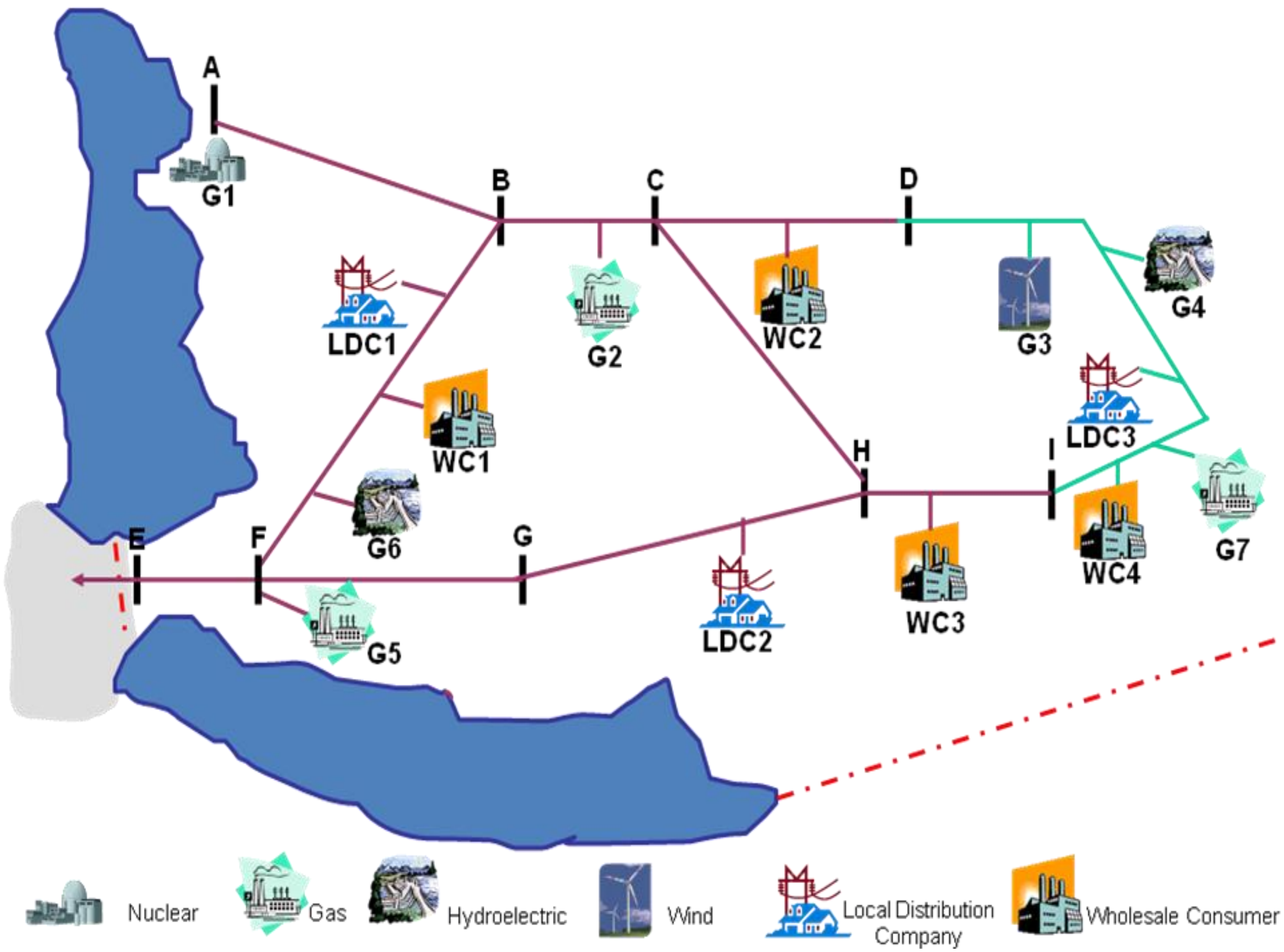

Figure 2: After the Blackout

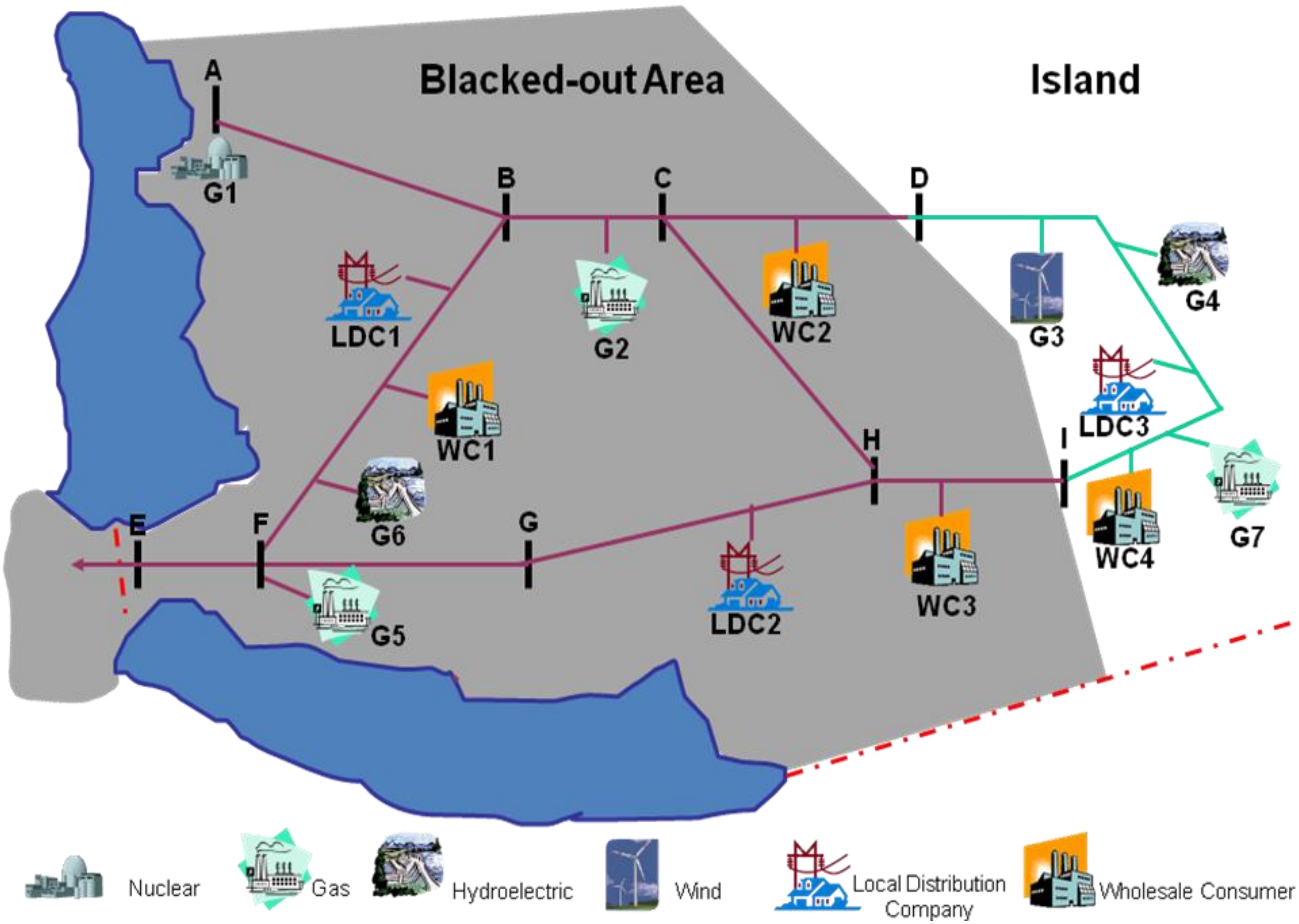

Figure 3: Where Should We Start?