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Emergency Generators for Resilient Response to Natural Disasters

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SUMMARY

Alberta is one of the Canadian provinces most prone to natural disasters. Wildfires and floods have become a quasi-annual occurrence in many locations across the province. Many of the past events were widespread and caused in transmission or distribution line damage, leaving areas temporarily separated from the Alberta Interconnected Electric System (AIES) until one or more of the affected structures could be repaired and restored. In view of the drives created by advances in power system resiliency and the expectation of a better service quality, modern day utilities must transition from a traditional reactive response, often involving trailing generator buildings and diesel tanks to a site after disaster has struck or is imminent, to a more proactive and efficient measure. This paper addresses the challenges associated with the system planning for temporary emergency situations related to natural disasters. It includes the theory behind the required equipment sizing and specification, strategies to pre-position and allocate mobile emergency generation assets, and grounding and protection considerations.

KEYWORDS

Back-up Diesel Generators, Resiliency, Emergency Response.

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BACKGROUND

Major natural disasters such as earthquakes, tropical storms, tsunamis, ice storms, flooding, and wildfires have caused severe power outages around the world in the last few years. In Alberta, similar events include the 2011 Slave Lake fire, 2016 Fort McMurray fire, 2017 La Crete floods, the 2019 Northern Alberta wildfires that affected High Level, La Crete and Wabasca, and the 2020 floods in North Alberta.

Natural disasters have warranted a paradigm-shift for many electric utilities. When a ‘secure state’ changes to an ‘alert state’, the focus shifts to attempting to minimize the impact of catastrophes and immediately implementing recovery actions to reduce supply interruptions. Being a provider of one of society’s most critical services, it is natural and expected that electric utilities would focus on becoming more resilient. One of the guiding technical entities in this subject, IEEE PES has released many related technical reports and standards. Its Industry Technical Support Task Force defines ‘resilience’ as, “[t]he ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event” [1]. This technical report also specifies that utilities, in particular electric utilities, must be able to tolerate the straining caused by a natural disaster and recover as quickly as reasonably possible and with justifiable financial expenditures. In a practical world, however, it is impossible to completely avoid any performance degradation when a disaster occurs. A proactive and appropriately developed strategy containing adequate countermeasures and response plans probably represent the best course of action to improve system restoration.

Recent past events, such as those explained above, have instilled many utilities to give a thorough look into their emergency preparedness strategies, resulting in a wealth of literature in the current subject. For example, the authors of [2] have reviewed how natural disasters have damaged much of the Chinese electric power grid infrastructure. The authors of [3] have presented the lessons learned from the 1994 earthquake in California, and the authors of [4] published an overview of the impacts of the 2010 Chilean earthquake. The recovery from a 1993 severe weather-related water damage in Missouri was presented in [5]. An overheating-related weather event in New Zealand was presented in [6].

Natural disasters have always been present and gradually posed more challenges to infrastructure owners as their asset pool grows. But, in fact, emergency preparedness has been a long-standing practice for most electrical utilities, as demonstrated in a research published in 1955 [7]. While power systems were more rudimentary back then, it is important to highlight proponents of great measures to counter disaster-related loss of supply. Power systems have since them evolved greatly, as well as operational and maintenance practices. More recently, the authors of [8], having their focus narrowly defined on densely populated urban areas, presented an approach to pre-position and allocate generation assets. The pre-positioning is done early, once an area has been deemed to be prone to natural disasters, and the allocation is the last leg of dispatch and to be done in real-time, after the disaster is imminently close or has already struck. The authors in [9] propose a distribution grid hardening strategy based on the concept of the adoption of microgrids. This is an example of a future-looking approach that may become pertinent once microgrids gain widespread adoption.

While there have been theoretical and practical developments focused on elements of densely populated urban areas, such as road traffic congestion and foot traffic, rural areas in Canada present a unique challenge, with very limited experience made publicly available. This article presents a technical view on deploying emergency generators in response to natural disasters in Alberta. It summarizes the technical challenges and practices developed by a major electric utility to tackle natural disasters in the rural areas in the north of the province by employing mobile emergency generators. It addresses asset specification, system sectionalizing, generator allocation, and safety.

ENERGY BALANCING OF LOAD AND GENERATION

It is imperative to ensure that all the critical loads are continuously supplied. The preference is to transfer loads to feeders emanating from other substations that were not affected. If the alternate supply is unavailable, mobile generators must be employed. When sizing emergency generators, energy balancing represents one of the most challenging tasks to restore supply. The main considerations are addressed in this section.

A. Load Classification

To make effective use of all available generation resources, a thorough load plan must be developed. Each load must be categorized under at least three tiers:

- Tier 1 (Critical): Fire Stations, Hospitals, police stations, water treatment plants, pharmacies, telecommunication towers, grocery stores.
- Tier 2 (Desirable): Residential houses, schools, farms.
- Tier 3 (Non-essential): Industrial processes and non-essential commercial buildings.

B. Supply Continuity

The reconfigured system may require each feeder to be supplied by one or more generators. Furthermore, each feeder may need to be separated into even smaller islands that are supplied by their own generator sets.

Commercial load flow programs such as CYME are the most suitable tool to ensure:

- Appropriate sizing of generators.
- Reliable protection philosophy.
- Maintaining adequate system voltage. Power quality requirements may be relaxed.

Generator Sizing

Adequately sized generation needs to be available in (each of) the distribution grid section(s). This results in generator sets sufficiently large to supply all critical loads, and at least most of the desirable loads. Load imbalance must be accounted for to ensure the generator rating is not exceeded. Reliability and available standards may can be adjusted to fit the needs under such a condition.

Fuel Security

Fuel tanks are normally mounted along the generators. There must be sufficient fuel stored at the generator locations to ride through the disaster, or available road networks to allow refueling. Because of the temporary and mobile nature of the electricity supply, the generators will likely be internal combustion diesel fueled, as opposed to natural gas. If natural gas is available, however, gas-fired generators should be considered, to hedge against the risk of unavailable supply. Other forms of generation are not yet part of most utilities' mitigation plans.

Reliability and Availability

Best effort shall be employed to serve critical loads and desirable loads. To note, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency (SAIFI) are not accounted for during large events, when periodic reporting to Utility Commissions is completed.

Distribution System

The resulting distribution grid must have capacity to supply any power system islands that are created due to the emergency. Topological information, such as conductor sizes, must be considered when allocating the generators. Typically, distribution conductors have less ampacity away from a substation location. As a result, a generator installed far away from the substation could result in overloading conductors or low voltages. While spending must be prudent and distribution systems cannot be overbuilt, it is reasonable to have reasonable reinforcement to infrastructure if located in an area predisposed to disasters.

SYSTEM CONFIGURATION REQUIREMENTS

Generator Winding Configuration

Most mobile diesel generators are configured either as Δ or Y (ungrounded). These configurations provide better continuity and will not contribute to a ground fault, initiating alarms rather than tripping. When coupled with Yg-Yg transformers, a Δ or Y generator is not suitable to supply phase-to-ground connected loads. The equivalent sequence network of this configuration is shown in Fig. 1a. As a result, Y or Δ generators require an additional ground source. Conversely, Fig. 1b shows the sequence network of an Yg generator supplying a single-phase load. Z_{g1}, Z_{g2}, and Z_{g0} are the equivalent generator sequence impedances. E_{g1} is the generator positive-sequence equivalent voltage, Z_L is the equivalent load impedance, and I_L is the load current. Z_n is the neutral grounding impedance of the generator (zero if solidly grounded).

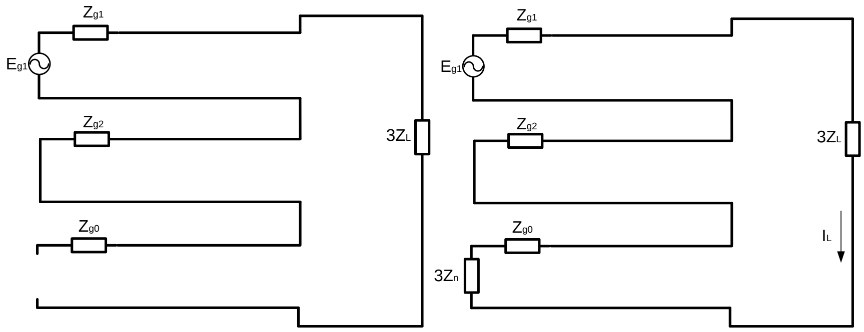

Fig. 1. *Sequence network of a generator supplying a single-phase load, (a) Y generator (b) Yg generator*

Transformer Winding Configuration

The transformer configuration plays an important role on the suitability of the supply. One case is a generator missing a ground source (Y or Δ), which requires an additional ground source, such as a Yg-Δ transformer (Δ in the low side), as illustrated in Fig. 2a. Another suitable configuration is shown in Fig. 2b, where the generator is configured as a Yg and coupled with a YgYg step-up transformer.

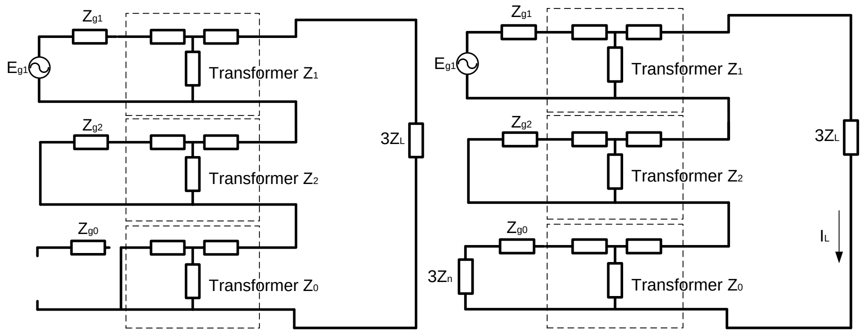

Fig. 2. *Sequence network of a single-phase load supply, (a) Y generator and Yg-Δ transformer, (b) Yg generator and YgYg transformer*

A grounding transformer can also be used to enable a configuration that does not contain a ground source. A grounding transformer, such as an Yg-Δ (low side Δ), can be used to provide zero-sequence current, allowing supplying single-phase-to-ground loads. Table 1 summarizes the generator-transformer combinations and indicates their suitability to supply single-phase loads.

Table 1 Generator-transformer configurations

		Transformer Configuration								
		Yg-Yg	Yg-Y	Yg-D	Y-Yg	Y-Y	Y-D	D-Yg	D-Y	D-D
Generator	Y	NO	NO	NO	NO	NO	NO	YES	NO	NO
	Yg	YES	NO	NO	NO	NO	NO	YES	NO	NO
	D	NO	NO	NO	NO	NO	NO	YES	NO	NO

Grounding Transformer Configuration and Design

A grounding transformer provides a low impedance zero-sequence path, supplying single-phase loads and zero-sequence current during a ground fault. Where appropriate and necessary, a grounding transformer can be designed and constructed with available transformer tanks. The transformer tanks should be configured as Δ-Yg (high side Yg). The grounding transformer must be sized as per [10], which prescribes the minimum design requirements for through-faults. According to [10], the damage curve of a 225 KVA grounding transformer was calculated and shown in Fig. 3 (inverse curve). It is compared with the fault current during a short-circuit study using CYME (straight vertical line). This can pinpoint the exact fault clearing time to avoid damage to the grounding transformer.

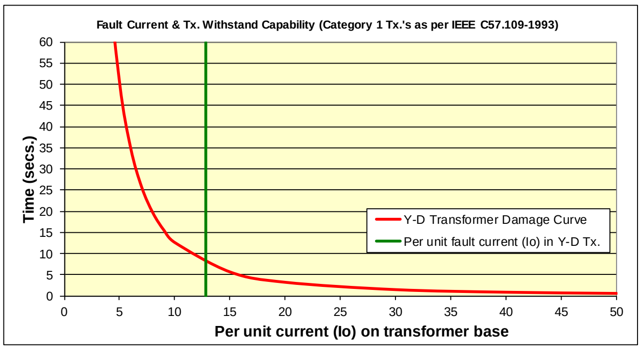

Fig. 3. *Grounding transformer damage curve and fault contribution*

Generator Ground Fault Detection

Automatic generation disconnection in the event of a ground-fault at the generator terminals may not be a code requirement if confined to an ungrounded secondary [11]. Detection of such a fault, however, is required. Normally, audible and visual devices are used to alarm a ground fault condition. Most diesel generator sets include ground fault detection and alarming, which may be very sensitive for Y or Δ generators. It could also be set to initiate a trip. If it is necessary to ground the neutral point of the generators to allow the supply of single-phase loads (explained earlier), protection elements may set off alarms excessively, or trip a unit under normal system condition, such as a motor start.

Reduced Fault Current

A small generator has a very different short-circuit characteristics from those of a large generator or a substation, with much smaller magnitude. A concern is whether this small fault current and duration will be enough to activate overcurrent elements. For this reason, it is best to site generators as close as possible to load. Prior to including a generator in an emergency fleet, it is important to gather and analyze fault characteristics from generator specification sheets or manufacturers' tests.

Generator Built-in Protective Elements

Small generators may not provide short-circuit currents large enough to maintain protection dependability. Counter-measures are:

- Rely on generator built-in undervoltage and underfrequency elements, allowing the generator to sense and trip for faults on the distribution system. This results in loss of selectivity and coordination. Time delays are needed to avoid spurious trips to inrush or motor starts.
- Sectionalize the distribution system into as small as possible segments, siting generators close to load and reducing the need for selectivity. Hence, voltage and frequency elements become the primary protection group.

Motor Starts and their Impact

A starting motor behaves as a constant (locked rotor) impedance and results in starting torque proportional to the square of the motor voltage. The starting power factor is low, often below 15%. Generator manufacturers will sometimes have guidelines on how to calculate the largest size of a motor that can be started by the generator, without causing nuisance trips. Two rules-of-thumb are:

1. Motor size to generator size ratio not exceeding 0.5 HP/kW [11]
2. Voltage across generator terminals above 0.75 p.u. during start

Shunt Capacitor Banks
Shunt capacitor banks are commonly used to support system voltage. When connected to the grid, they support the voltage along a feeder and reduce conductor losses. Under contingency, much of the load is curtailed and residents evacuated. If capacitor banks remain connected, surplus reactive power is likely to exist and be absorbed by the generator, leading to an under-excited operation. For this reason, all shunt capacitors should be disconnected from the system under emergency.

Arc Flash
It is important that the generators have their motor control center electric panels assessed for arc flash incident energy and minimum approach distances. Where they need to be accessed by field personnel, appropriate personal protective equipment must be worn.

CASE STUDIES

This paper presents a case of generators being deployed during the 2019 wildfires in Alberta. The affected communities were exposed to prolonged outages as the transmission lines supplying the substations were damaged. *Substation 1* lost its two wood pole transmission lines supplies (TEW and TNS), whereas *Substation 2* is radially fed by *Substation 1* through transmission line TR. Fig. 4 displays the configuration. TEW was severely damaged, but quickly reenergized with sections still leaning. Meanwhile, crews conducted repairs to TNS. Upon completing the repair of TNS, crews could then take TEW out of service to complete its reconstruction. The wildfires could not be controlled and subsequently burned several sections of both lines during a period of several days.

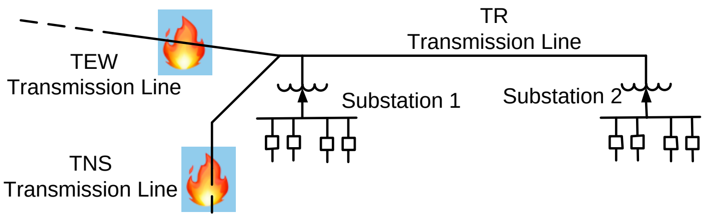

Fig. 4. *Configuration of the affected system*

Substation 1
Substation 1 mainly feeds a town and its surrounding rural areas. Fig. 5 shows the distribution system configuration and where emergency diesel generators were placed, i.e., near the substation. This allowed tying their ground grid to the substation grid. The high side of each generator transformer was fitted with very small fuses (similar in size to nominal load). Without major industrial customers and some of the residents prepared to evacuate, the load experienced a reduction.

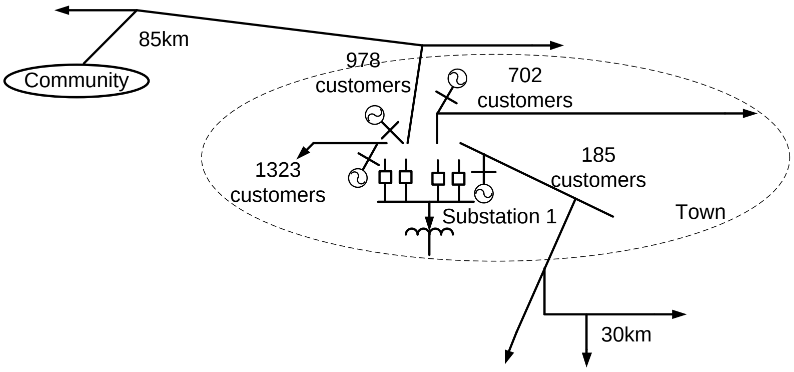

Fig. 5. *Substation 1 Configuration and Generation Deployment*

Substation 2
Fig. 6 illustrates the configuration of the system supplied by *Substation 2*. Four feeders emanate from the substation, two of them being exceptionally long and supplying four communities and a spread of

rural customers. The customer count at each feeder is also displayed in the figure. The generators were placed near the substation and in town. The utility used farm land to site the units. Where possible, generator ground grids were tied to that of the substation. Furthermore, the generator buildings were barricaded to avoid public access. With a reduced short-circuit level, none of the inline reclosers was sensitive enough to sense the new fault levels. The primary protection group became the generator undervoltage and underfrequency elements. Fuses were installed on the distribution feeder heads and sized to match the historical peak load. At the same time, the customers were encouraged to conserve electricity through public announcements. All industrial customers were directed to stop operation.

One feeder supplying three communities supplies 1356 customers and is 164 km long. *Community 2* is 122 km away from the substation. This community contains a back-up generation plant because it used to be isolated and was interconnected about a decade ago. Distribution utilities cannot own distributed generation but could retain this plant due to reliability issues as the community is only accessible by winter road. *Community 2* was to be disconnected from the feeder during the emergency scenario to allow better voltage management and powered up by its back-up plant. *Community 3* is about 162 km away from the substation and used to be isolated from the grid as well. It was interconnected 2 years ago, and its original diesel plant was dismantled.

The feeder that supplies the main load center was broken down into three smaller islands. It was decided that two of these islands could be better supplied using diesel generators placed in two locations. This option resulted in a better voltage management.

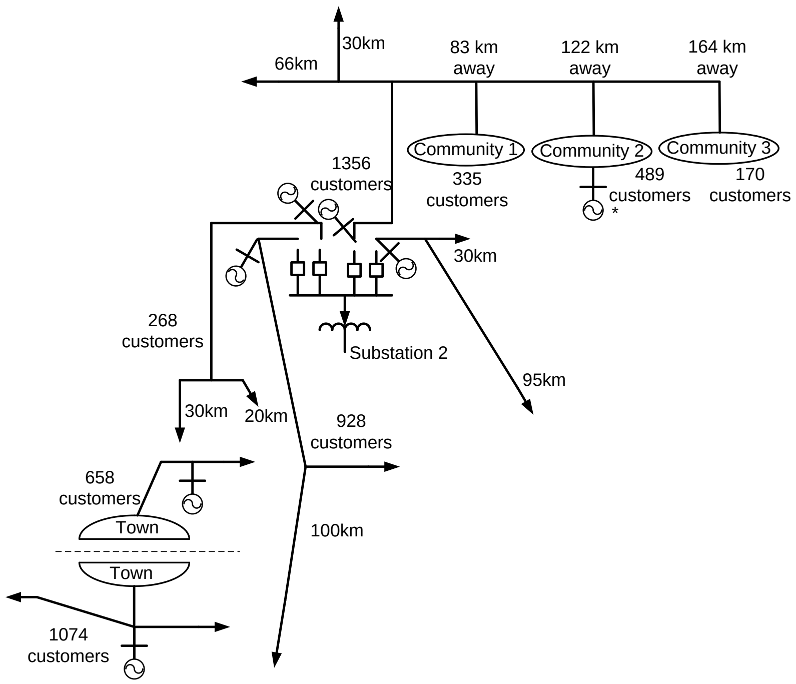

Fig. 6. *Substation 2 Configuration and Generator Placement*

CONCLUSIONS AND LESSONS LEARNED

Before the real-time allocation and installation of emergency generators, the utility tried to maximize the usage of its existing fleet of generators and transformers. This led to many lessons learned.

Transformer and Generator Technical Requirements

- A ground source is required at the distribution feeder level. The generator-transformer configurations must be one of the options shown in Table 1. The use of generator or transformer neutral ground resistors (NGRs) must be avoided.
- A grounding transformer may be required.
- The primary protection group becomes the generator built-in voltage and frequency elements.

If equipment is being rented, it is recommended to be secured as a complete generator-transformer set.

Grounding and Safety Requirements

Where possible, the ground grid of the generators must be tied into that of a substation to improve performance and safety grounding. Foot traffic can be restricted by erecting wood fences and tape barricades around the installations. A grounding study is recommended to determine the step potential.

Access Roads

Wildfires may compromise road access, jeopardizing equipment and fuel delivery. This is a contingency that must be considered in the emergency response planning and management.

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