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A Comprehensive Analysis to Create and Operate a Temporary Power System Island – A Real Case Study

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SUMMARY

Due to different reasons such as limited access and financial considerations, some regional substations may radially connect to the bulk transmission system. Radial connection provides no redundancy as an outage on the radial path would take corresponding substations out of service. As a result, alternate supply solutions would need to be arranged before taking long outages on the radial path. One form of such solutions is to connect a temporary generating station and form a small island to feed the involved substations. A set of studies and analyses must be performed to ensure safe and reliable operation of such island. This paper uses a real example and presents some of the key analyses that must be done.

In the real example, a transmission line radially supplying two load substations was to be taken out for a few months for a line rebuild project. A temporary generating station was planned to form an island and supply those load substations. The paper presents the analysis that was performed to identify the best timeline to create the island, and determine the size and the number of required generators and their reactive power requirement. Considerations and challenges for connecting the generating station such as transformer configuration and grounding arrangements, and control of voltage, transformer tap changers and load banks are discussed. This paper also presents frequency scan studies to determine and compare the resonance points of the island configuration with those of the normal grid connection. The highlights of the protection scheme and applicable settings are presented as well. In addition, the paper discusses the precautionary actions taken prior to creating the island and during the island operation to ensure successful operation of the island. The process presented in this paper to create and operate the island provides a general guideline to create power system islands in future.

KEYWORDS

Power system islands, Temporary generating station, Transmission line outages

1. Introduction

Transmission systems are typically planned in meshed topologies in order to provide redundancy in case certain lines go out of service due to forced or planned outages [1]-[2]. However, due to different reasons such as limited access and right of way, some regional substations may radially connect to the bulk transmission system. Radial connection provides no redundancy as an outage on the radial path would take corresponding substations out of service. As a result, alternate supply solutions would need to be arranged before taking an outage on the radial path.

As a real example, two substations in the Banff National Park, Alberta connect to the transmission system via a single radial 69 kV transmission line. This radial line needed to be rebuilt as it was reaching its end life. Due to the strict limitations imposed by the Parks Canada, it would not be possible to construct the new line on a new and different right of way. In other words, the new line would have to be constructed on the same right of way as the existing line, and as a result, a few months outage was needed on this radial path. To facilitate this line reconstruction, a temporary configuration as shown in Figure 1 was arranged, which involved operating an island of a temporary generating station, two load substations and a 69 kV line. This paper will present the analysis and studies that were performed to create and operate this small power system island. In summary, the following will be presented and discussed in this paper:

- Load profile analysis of the two load substations to determine the best time for the outage and determine the size and number of generators and their reactive power capability during island operation.
- Considerations for connecting the generating station such as transformer configuration and grounding arrangements, and control of voltage, transformer tap changers and load banks.
- Frequency scan studies to determine and compare the resonance points of the island configuration with those of the normal grid connection. This analysis determines the minimum number of generators that must be online at all time.
- Protection scheme designed for this island operation, including modifications to the existing protection system as well as new frequency and voltage protection schemes.
- Considerations and recommended steps to energize the island such as locking transformer tap at Sub 1 to prevent voltage hunting between generators and the transformer and calculating transformer tap position at Sub 1 to avoid high voltage at Sub 2 during the energization of 69 kV Line 1.

In addition, this paper presents a summary of the precautionary actions that were taken to reduce the likelihood of faults/failures during island operation.
The analysis and discussions presented in this paper for this particular case study can also be used as general guidelines for future applications where a temporary power system island is to be created and operated.

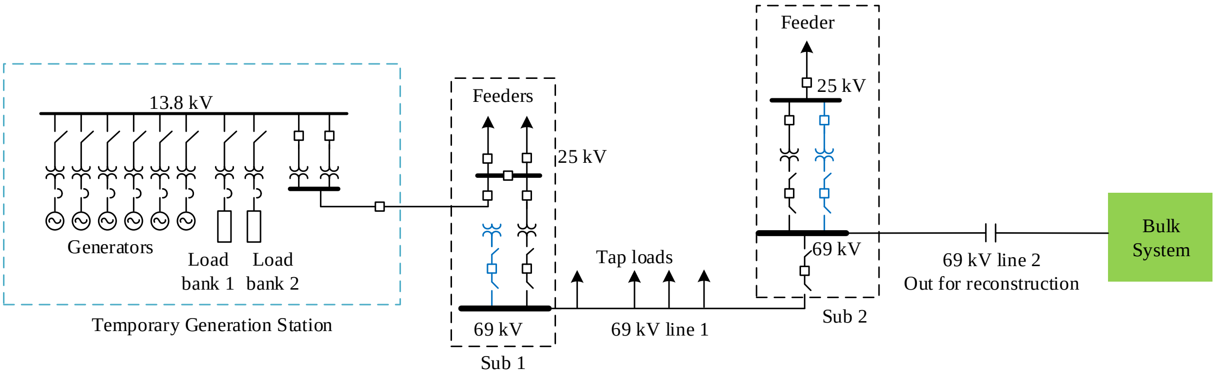


Figure 1: Table System topology during the island operation

2. Load Profile Analysis

Load profile analysis is a key step that will help choose the best timeframe for the outage, and determine the size of generators and their reactive power capability. For this purpose, it is important to accurately estimate the maximum and minimum expected load of the island, understand the load characteristics such as inductive/capacitive nature of the load and potential presence of harmonics, possible reactive power fluctuation of the island, seasonal and daily load variation pattern, possible load fluctuations due to disturbances and maximum possible load pickup when restoring after disturbances. Furthermore, available space for generator set up, challenges of transportation of the generators and their fuel and the storage capacity of fuel play an important role for sizing generator as well.

Historical load data of the two substations and 69 kV line 1 tap loads over a four year period were analyzed to determine the maximum and minimum expected load of the island. Figure 2 shows the daily maximum and minimum load for the four year period. It can be observed that the daily maximum load is significantly lower during mid-May to mid-October timeframe. The variation between maximum and minimum daily load is also lower during this period. Therefore, it would be better to create the island during this timeframe as the impact to the customers would be minimum and the total generation supply requirement would be lower. As a result, mid-May to mid-October timeframe was selected for performing the work as it could reduce the project cost significantly and would lead to easier coordination with the customers. Also, the right of way of the transmission line is more accessible during the summer time.

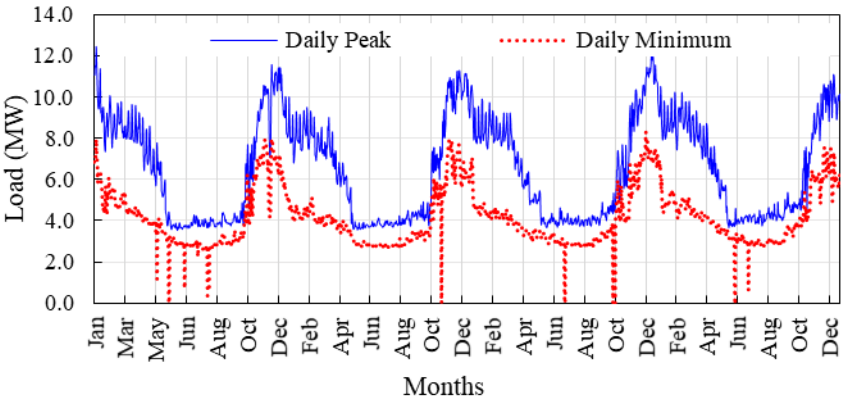


Figure 2: Historical maximum and minimum load for Sub 1, Sub 2 and 69 kV line 1 taps

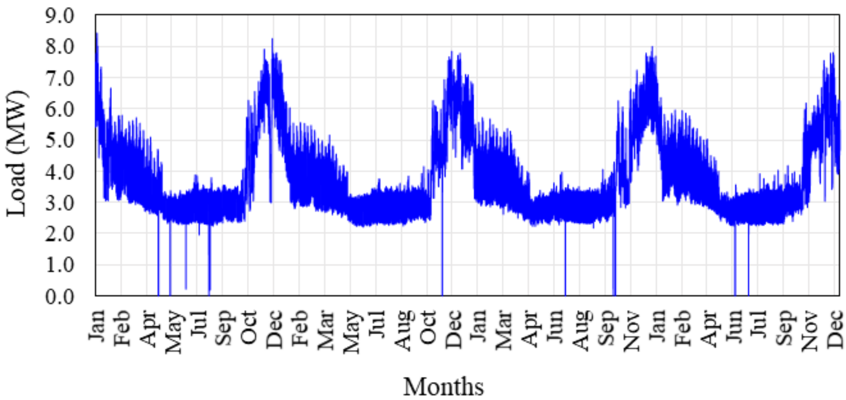


Figure 3: Historical load for Sub 1

The line rebuild project was planned in two main stages including Stage 1 rebuild of line 1 and Stage 2 rebuild of line 2. As a result, in Stage 1 the island would only consist of the loads at Sub 1, and in Stage 2, it would include all the loads of Sub 1, Sub 2 and tap loads of line 1. Therefore, the maximum expected load for the island would be during Stage 2 and according to the four year data shown in Figure 2, the maximum load during the proposed timeframe of mid-June to mid-October is 5.7 MW. The minimum expected island load would be during Stage 1 which would be 2.0 MW, when supplying only Sub 1, shown in Figure 3.

In addition to the load profile discussed above, the following factors were also considered in determining the number and size of generator units.

- Based on the information received from the generator owner, it would be best to operate diesel generator units above 60% of their capacity all the time to deliver the power at improved efficiency [3].
- To provide higher short circuit strength, it would be better to have more than one unit online at any time. In addition, frequency scan studies that will be presented later recommended that minimum three generators should be in service at any time.

With respect to the above, total 6 diesel generator units (5 + one stand by generator) with 1.825 MW capacity was considered for this project. A 3.0 MW of variable load bank, one 2.0 MW and one 1.0 MW, were also installed to maintain the online generators output above 60% in case the total island load is below 60% of the total capacity of the online generators.

The reactive power consumed by the two substations are also analyzed. Figure 4 shows yearly reactive power variations at the two substations. Both substations are supplying remote load and the load of ski resorts. It can be observed from Figure 4 that during winter season when ski hills are operating the reactive power varies between inductive and capacitive. However, during summer time, when ski hills are closed the load remains capacitive. The main reason for the capacitive characteristics of the load is capacitor banks ski resorts have installed for power factor correction. In addition, the feeders of the two substations are supplying remote loads far from the substations, and as a result, the length of the feeders are also contributing to the capacitive load.

Since the line rebuild was done during summer time, to reduce the VAR consumption by the generator units during island operation, the customers were requested to turn off their capacitor banks. Switching off the customer capacitor banks will also reduce the possibility of resonance creation during island operation which has a weaker source compared to that of the system.

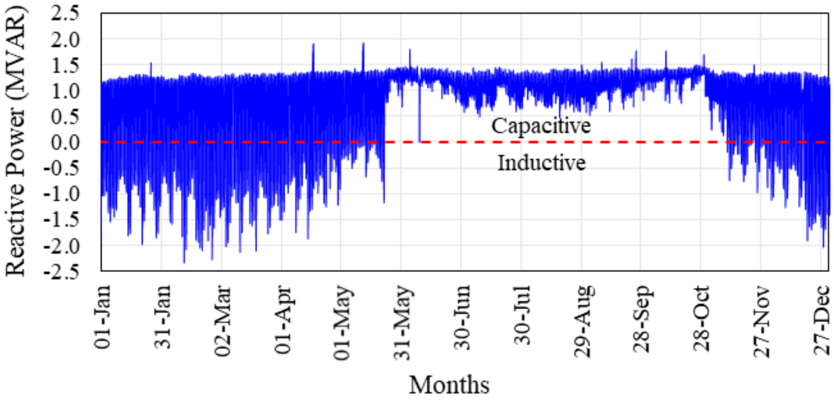


Figure 4: Yearly historical reactive power of Sub 1, Sub 2 and 69 kV line 1 taps

3. Configuration and Considerations of the Island Set up

The temporary generating station is setup beside Sub 1. The location of the temporary generating station was determined based on the available space nearby the substation. A detailed ground grid design study was conducted to ensure the ground grid at the generator laydown area meets applicable criteria such as IEEE Std. 80-2000 [4]. Figure 5 shows the single line diagram of the temporary generating station setup. As the figure shows, the generator voltage is 480 V and the six generator units are connected in parallel to a 13.8 kV bus via six 480 V/13.8 kV Y-Y solidly ground step up transformers. The 13.8 kV bus then connects to the 25 kV bus of Sub 1 via two parallel 13.2 kV /25 kV delta-delta transformers. During operation only one transformer is planned to be in service and the other transformer is to be left de-energized to provide redundancy. The delta-delta transformer configuration blocks the third harmonic component in the secondary voltage [5] which gives more sinusoidal voltage at 25 kV bus. The drawback of this configuration is that no ground will be provided for the island i.e. on the 25 kV side of the transformer. To mitigate this problem, a grounding transformer [6] is arranged to be connected to the 25 kV side of the transformer as shown in Figure 5.

Voltage settings are set as follows. Generator AVR is set at its nominal terminal voltage of 480 V and considering the tap position of the generator step up transformers, the voltage at 13.8 kV would be set at 13.2 kV. The tap changer of 13.2 kV/25 kV transformer is set to a fixed tap to obtain 25.7 kV voltage at the 25 kV bus at Sub 1. This voltage level was chosen in coordination with the DFO (Distribution Facility Owner) to ensure it is high enough for the customers and at the same time to avoid any damage to the distribution customers due to over voltage during any load changes in the island.

As explained in the previous section, in Stage 1 only the load at Sub 1 is connected to the island. During this configuration, the island load is expected to stay within 4.2 MW and 2.0 MW. On the other hand, the frequency scan studies that will be presented in the next section recommended the minimum of three generators to run all the time during the island operation. The generators are not expected to run below 60% of their maximum capacity as per manufacturer’s recommendation. In order to make all these requirements possible, two variable load banks including a 1 MW resistive and a 2 MW resistive/reactive load bank are used at the generating station. The load banks are equipped with automatic controllers to adjust the load settings automatically based on the island load variation. These controllers are coordinated with the generators’ governors to ensure the island frequency is always close to 60 Hz while generating units are always running above 60% of their capacity.

In the second stage, the load at Sub 1, Sub 2 and 69 kV line 1 taps are connected to the island. During this stage, 69 kV line 1 is energized from Sub 1. Prior to the energization, the 25/69 kV transformer tap was set to a fixed tap position to avoid any voltage hunting between the generator AVR and the transformer’s automatic tap changer. The transformer tap position was determined based on power system studies such that no high voltage occurs at the Sub 2 end of the 69 kV line 1 during line energization.

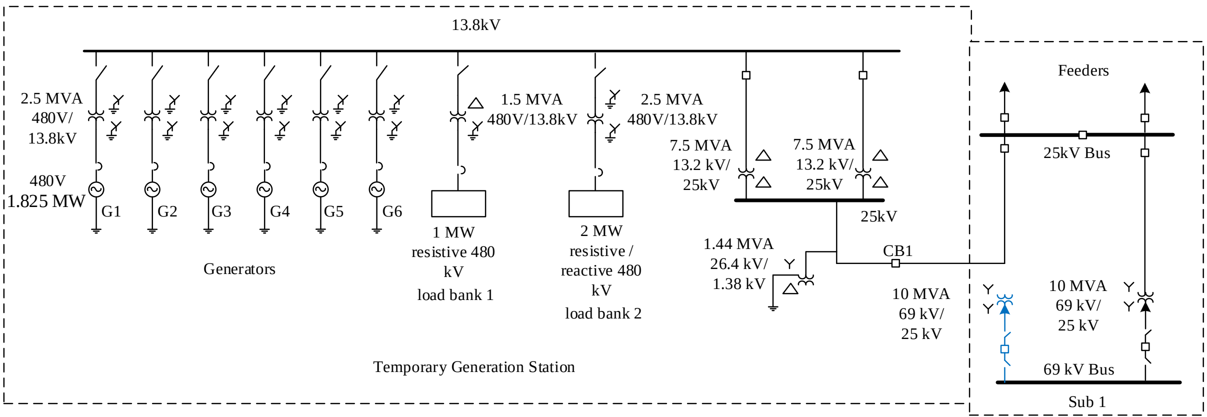
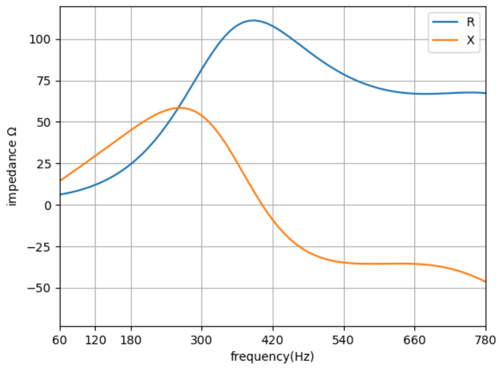


Figure 5: Single line diagram of the temporary generating station set up

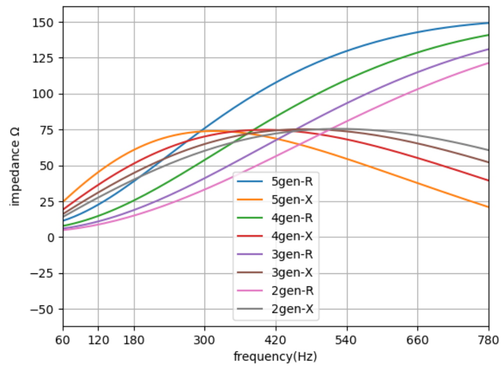
4. Frequency Scan Study

The inductance and capacitance of different elements in any power system interact with each other. Their interaction can create resonance points. If parallel resonance points line up with characteristic harmonics, the impedance and subsequently the harmonic voltage can become very large [7]-[8], especially when those characteristic harmonics are low order which may have significant harmonic current injections at those frequencies. This can lead to violations of the limits specified in industry standards, and consequently poor quality of power being served to the customers, which may impose risk of equipment failure as well. Therefore, whenever system configuration is to experience significant changes such as in our case where a new island is to be created, it is important to conduct required studies to ensure no unsafe parallel resonance could exist.

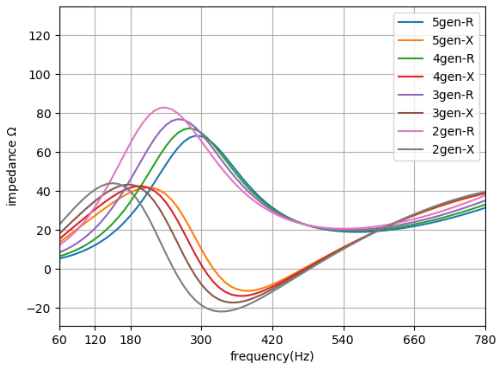
As a part of this project, frequency scan analysis was performed to compare the harmonic impedance at different buses between the usual grid operation and the intended island mode operation. The study results for 25 kV bus at Sub 1 are shown in
Figure 6. As this figure shows the harmonic impedance calculated at 25 kV buses during island operation is comparable to the harmonic impedance during grid operation. Therefore, the configuration change is not expected to cause significant increase in the impedance at low order harmonics and therefore no concern exits.



(a) Usual grid operation



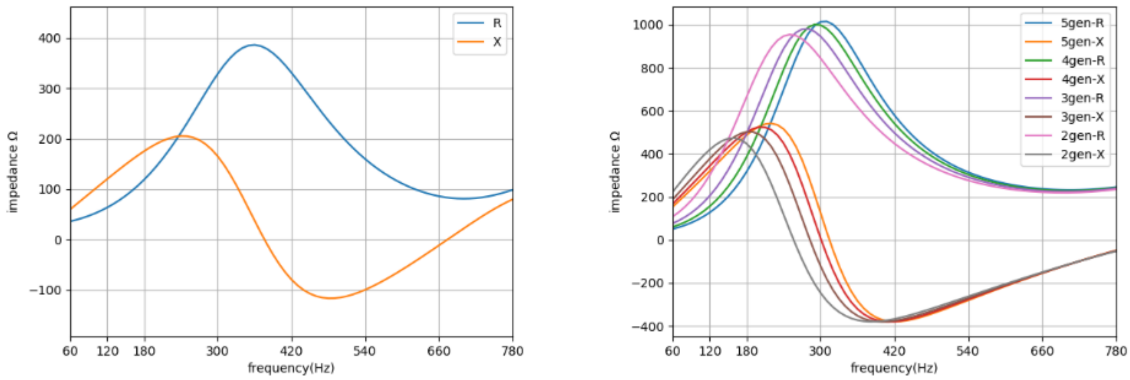
(b) Stage 1 of island operation



(c) Stage 2 of island operation

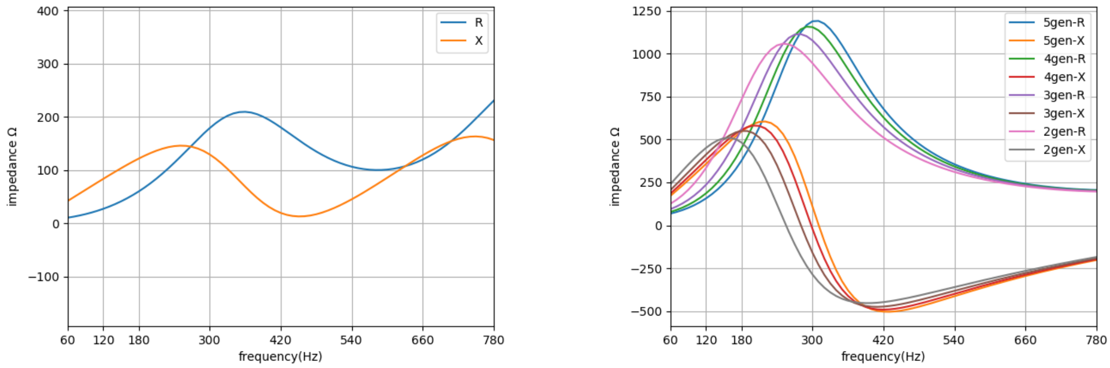
Figure 6: Frequency scan results at 25 kV bus at Sub 1

Figure 7 and Figure 8 show the harmonic impedance at 69 kV buses at the two substations. As these figures show, the impedance during island operation is much higher than the impedance during grid operation. In addition, it can be seen that the number of online generators plays an important role in the location of the parallel resonance, i.e. having less number of generators can move the resonance point to lower order harmonics. In particular, with two generators online, the resonance can be two close to the fundamental frequency, which is a scenarios that should be avoided. As a result, it is recommended to have at least three (3) generation units in service all the time during the island operation.



(a) Usual grid operation (b) Stage 2 of island operation

Figure 7: Frequency scan results at 69 kV bus at Sub 1



(a) Usual grid operation (b) Stage 2 of island operation

Figure 8: Frequency scan results at 69 kV bus at Sub 2

5. Protection Scheme Design

Protection system sensitivity and coordination is necessary to maintain system stability and limit further damage to power equipment. Since the system topology and source impedance of the island is significantly different from that of the system during normal operating conditions, detail fault studies and protection coordination studies were performed to understand the fault current levels during the island operation, and adjust protection schemes and settings. Some highlights of these modifications are presented below.

In the normal system topology Sub1 and Sub 2 are connected to the grid and the 69 kV line 1 and line 2 are protected by distance protection elements located at the system source terminal. During the island operation, the flow on the line 1 reverses as the generators are connected on the load side of the radial line (Sub 1) to supply the island load as shown in Figure 1. Furthermore, Sub 1 does not have a 69 kV bus voltage transformer (VT). Therefore, a non-directional overcurrent protection was installed to provide L1 line protection functionality. In addition, the line auto-reclosing scheme was disabled due to system stability concerns.

The 13.2/25 kV transformer located at the temporary generating station, is equipped with an overcurrent protection designed to detect faults along the tie line. This protection is set to coordinate with the overcurrent protection on the tie breaker CB1. The settings of 25 kV feeders protection were also reviewed and updated as required. The automatic reclosing of the feeders were also blocked to avoid sudden large current changes that could trip the generators. A single shot manual reclose was permitted to test energize the feeder prior to dispatching a trouble response crew. This provide faster restoration times for transient faults.

In addition, over/under frequency and over/under voltage protection settings were implemented for the island operation. In a small island, a large frequency fluctuation may occur due to a small disturbance. Therefore, over/under frequency protection setting is required to maintain power quality within acceptable limits. In the case study, two sets of frequency setting were considered. A wider set of protection settings is implemented at the generator station (OF tripping: > 63.0 Hz for 10.0 sec. and UF tripping: < 57.0 Hz for 10.0 sec.) to prevent unnecessary tripping of the generators. This wider settings will give the generators an opportunity to adjust their speed before the relay operates. Another set of protection settings (OF tripping: > 62.0 Hz for 5.0 sec and UF tripping: < 58.0 Hz for 5.0 sec) was implement at the CB1 shown in single line diagram (Figure 5) which will trip off the island if power quality requirements are not met.

A large voltage fluctuation may also occur due to a disturbance during island operation. Therefore, over/under voltage protection settings should be carefully selected to avoid equipment damage as well as over tripping of the island. In the case study, the under-voltage tripping pick up value was set to < 23.1 kV (0.9 p.u. of nominal voltage of 25.7 kV) for 10.0 sec, and the over-voltage tripping setting was set to < 28.3 kV (1.1 p.u.) for 10.0 sec. To determine the optimum overvoltage setting, dynamic stability studies were performed for different fault types. The study results showed that, a three phase bolted close-in fault would cause the worst overvoltage for the studied case. The overvoltage observed at the generator terminal is >1.1 p.u. for 4.9 seconds after the fault is cleared by tripping off the faulted feeder.

6. Precautionary Actions Taken Before the Island Operation

To minimize the risk of faults and disturbances during the island operation, various precautionary actions were taken before creating the island. Some of these actions are summarized below.

- The duration of the island operation was shortened as much as possible. To do that, during the project planning stage, all the options were explored to shorten the outage duration and emergency restoration time. In addition, preparation work was completed as much as possible prior to the outage.
- The line construction work was staged and the construction spans were selected such that in case of emergency, the 69 kV line could be put back into service within eight (8) hours. This would minimize the impact to the customers in case the temporary generating station failed for some reason and would not be possible to return in quickly. In that case, the 69 kV line would be restored within eight (8) hours and the connection to the system would be restored. Alternate protection settings were in place to switch to normal supply from the system if required.
- Infrared (IR) scanning was completed for all the equipment at Sub 1 and Sub 2 to identify any issues that may cause problem during island operation. Any concern that needed immediate attention was mitigated before the island operation.
- 69 kV line 1 was aerial patrolled before the island operation to identify any potential fault hazard along the right of way such as trees leaning on the line. The aerial patrol was done frequently (every month) during the island operation to ensure no new hazard existed.
- A detail island operating procedure was developed that was used during island operation. The operating procedures includes all the possible fault scenarios and steps requires by different parties to restore the island load to minimize the customer impact.
- Once the island was formed, it was run for 24 hours before starting the line construction work to monitor the island operation such as the generators response with the island load fluctuation, distribution voltage, VAR consumptions etc. This would provide an opportunity to identify any potential concern and fix that before starting the line construction work.

7. Conclusion

Due to different reasons such as limited access and financial considerations, some regional substations may radially connect to the bulk transmission system. Radial connection provides no redundancy as an outage on the radial path would take corresponding substations out of service. As a result, alternate supply solutions would need to be arranged before taking long outages on the radial path. One form of such solutions is to connect a temporary generating station and form a small island to feed the involved substations. A set of studies and analyses must be performed to ensure safe and reliable operation of such island. This paper used a real example and presented some of the key analyses that must be done.

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- Protection scheme designed for this island operation, including modifications to the existing protection system as well as new frequency and voltage protection schemes.
- Precautionary actions that were taken to reduce the likelihood of faults/failures during island operation.

The process presented in this paper to create and operate the island provides a general guideline to create power system islands in future.

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