GRC Transactions, Vol. 42, 2018

Theistareykir Geothermal Power Plant, Challenges in a Weak Electrical Grid

Freyr Hardarson[1], Birkir Heimisson[3], Sigurgeir Björn Geirsson[2], Jón Arnar Emilsson[2], Íris Baldursdóttir[3] and Valur Knútsson[2]

[1]Mannvit, Consulting Engineers
[2]Landsvirkjun, National Power Company of Iceland
[3]Landsnet, Icelandic Transmission System Operator

Keywords

Geothermal Power Plant, Geothermal utilization, Transmission system, Governor, Steam supply

ABSTRACT

The challenges in operating Landsvirkjun's new 2x45 MW_e geothermal powerplant at Theistareykir in North East Iceland involve guaranteeing that the plant responds reliably with different scenarios that can arise in operation of the grid. The plant strengthens a relatively weak electrical grid in NE Iceland and provides electricity for high energy intensive industries in the area. The location of the plant is rather remote and connects to a single 220 kV transmission line going from Húsavík to Krafla geothermal power plant where it connects to the main grid.

Geothermal power plants in Iceland are generally run as base load whereas hydro plants handle fluctuations in grid load. The new plant at Theistareykir is, however, required to respond quickly to load variations and provide stability to the grid. In case the plant disconnects from the grid, means for quick recovery are necessary. These requirements arise from the following reasons: Maintaining a continuous supply of electricity to the industry area is essential to avoid production losses. As the industry area is by far the largest consumer of electricity from Theistareykir, any mishaps there have large effect on the stability of the grid. In addition, transmission line failures and other unforeseen disturbances can create situations where the plant is cut off from the main grid and islanded.

The efforts made to accomplish this goal include among other: The turbine units have been implemented with functions that enable the units to contribute to the control of grid frequency and, in situations where the area is cut off from the main grid, to actively control the islanded grid frequency. Design of the plant aims to guarantee that steam supply and auxiliary systems have sufficient redundancy and capability to handle varied operational conditions. The plant has been provided with black start capabilities to allow for energizing the power lines and transformers without any external power. Extensive tests have been done with the grid operator on the active grid to simulate the situations that can arise and monitor the response of the plant.

1. Introduction

Theistareykir Geothermal Power Plant was taken in full operation in April 2018. The power plant has two 45 MW_e turbine/generator units and utilizes steam from flashed geothermal fluid. The plant strengthens the relatively weak, low inertia, grid of the North-Eastern part of Iceland and provides energy to a newly established power intensive industry area at the town of Húsavík. The plant is located in a rural area approximately 25 km south-east of Húsavík, at an elevation of 330 m above sea level. The plant is connected to the electrical grid through a single 220 kV transmission line that extends from the industrial area at Húsavík to Theistareykir and continues to Krafla Power Plant where it connects to the 132 kV ring connection of the grid around Iceland, see Figure 1. Further description of the power plant and the history and development of the project can be found in Knútsson et al. (2018).

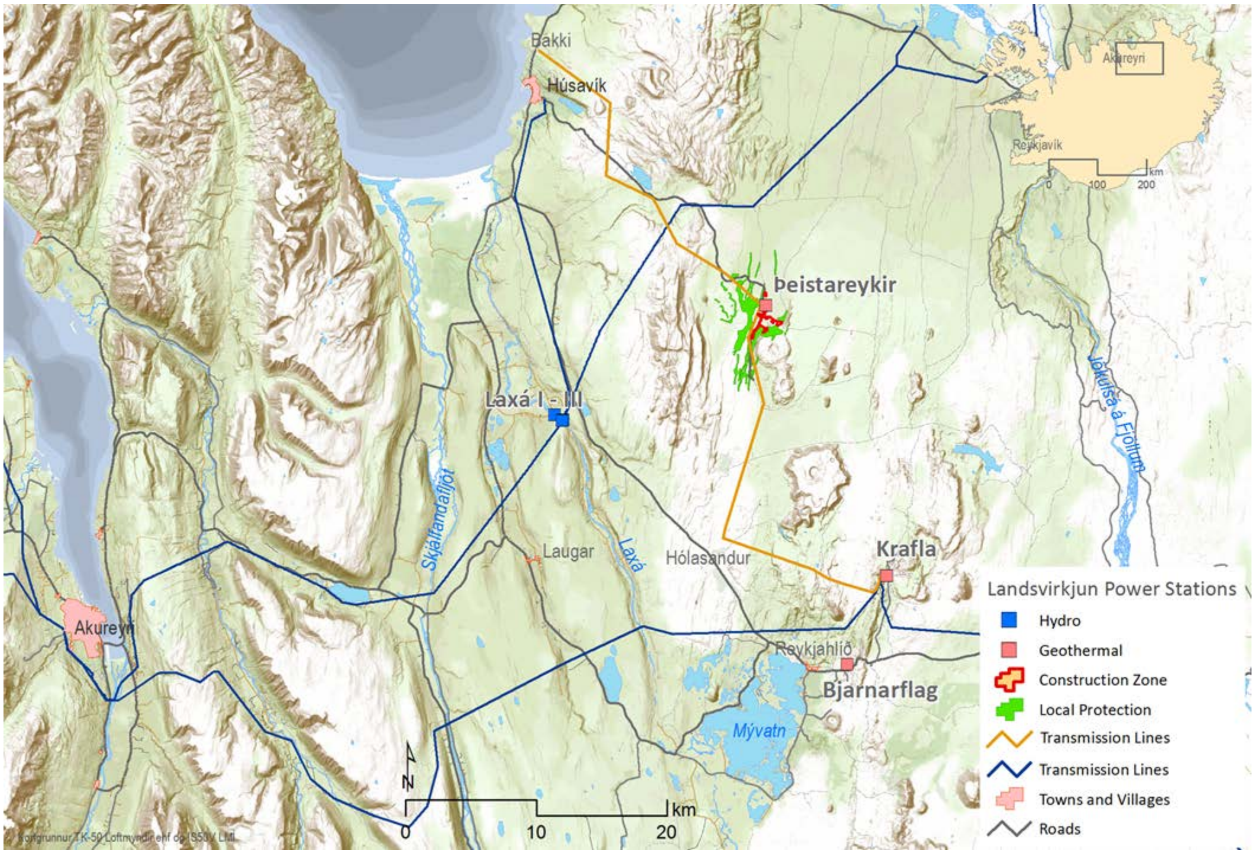

Figure 1: Overview of the power plant at Theistareykir and 220 kV transmission lines (orange) to Krafla power plant and Bakki, industrial area at Húsavík.

The main centers of power production in Iceland are in the South-Western and Eastern part of Iceland, that form 60% and 27%, respectively, of the total installed power production in Iceland. Approximately 80% of the produced power goes to industry, including power intensive industries such as aluminum and silicon smelters. The transmission system in Iceland interconnects these centers of power production with a 132 kV ring connection but there are severe capacity limits between the regions, most notably between the South-Western and North-Eastern part. Any unforeseen interruptions in either power usage, production or the transmission system in Iceland can lead to complex dynamic instabilities and power oscillations that can lead to cascading faults. In cases of instability, it can be necessary to open network switches and island regions, requiring power generation units to regulate the frequency within each respective island.

Geothermal power plants in Iceland are about 28% of installed power generation capacity in Iceland and are generally run as base load whereas hydro plants handle fluctuations in grid load. However, technically geothermal power plants have the potential to contribute to grid stability and flexibility in power balancing services, Matek (2015). This involves providing the turbine governor and the automatic voltage regulator (AVR) with the necessary functions to adapt to grid situations. In addition, the supply systems, most notably the steam supply system, need to be able to handle abrupt changes in a stable manner. Furthermore, combining the faster response of steam turbines with the response of the hydro plants has the potential to be beneficial for overall transmission system stability by coordinating the response of the units.

The main challenge involved in the operation of Theistareykir Power Plant is the weak electrical grid of in the North-Eastern part of Iceland, as there are no substantially sized hydro power units in the area and the limitations in the grid connection of the region. In normal operation Theistareykir Power Plant will provide base load for the industrial area at Húsavík, where a silicon smelter plant has been erected. The power plant is, however, required to react to varying operation conditions, such as frequency disturbances or islanding events, by contributing to grid stability or actively control the grid frequency. It can also be expected that severe events will trip the turbines and means for quick recovery are needed. Various requirements have been incorporated in the design of the plant to facilitate reliable operation of the plant.

This paper will provide an overview of Theistareykir Power Plant and describe the efforts made to provide the plant with the necessary functions for a reliable and stable operation. The paper will also describe tests that have been done, the response of the plant to various incidents in the grid and report on the ability of the power plant to contribute to grid stability.

2. Plant Overview

Theistareykir Geothermal Power Plant is comprised of following main systems: steam supply, turbine/generator units including the cold end (i.e. condenser, gas extraction systems, cooling water circuit), cold water supply and instrument air supply, see Figure 2. All main equipment is located indoors due to local weather conditions as heavy snow and winds can be expected. The power house contains the turbine/generator units, the cold end equipment, transformers, along with electrical distribution, and instrument air supply, as well as a workshop and other facilities for operation and maintenance of the plant. There are two buildings in the steam supply to house equipment, the steam valve house and the reinjection house. Finally, there are two buildings for the water supply.

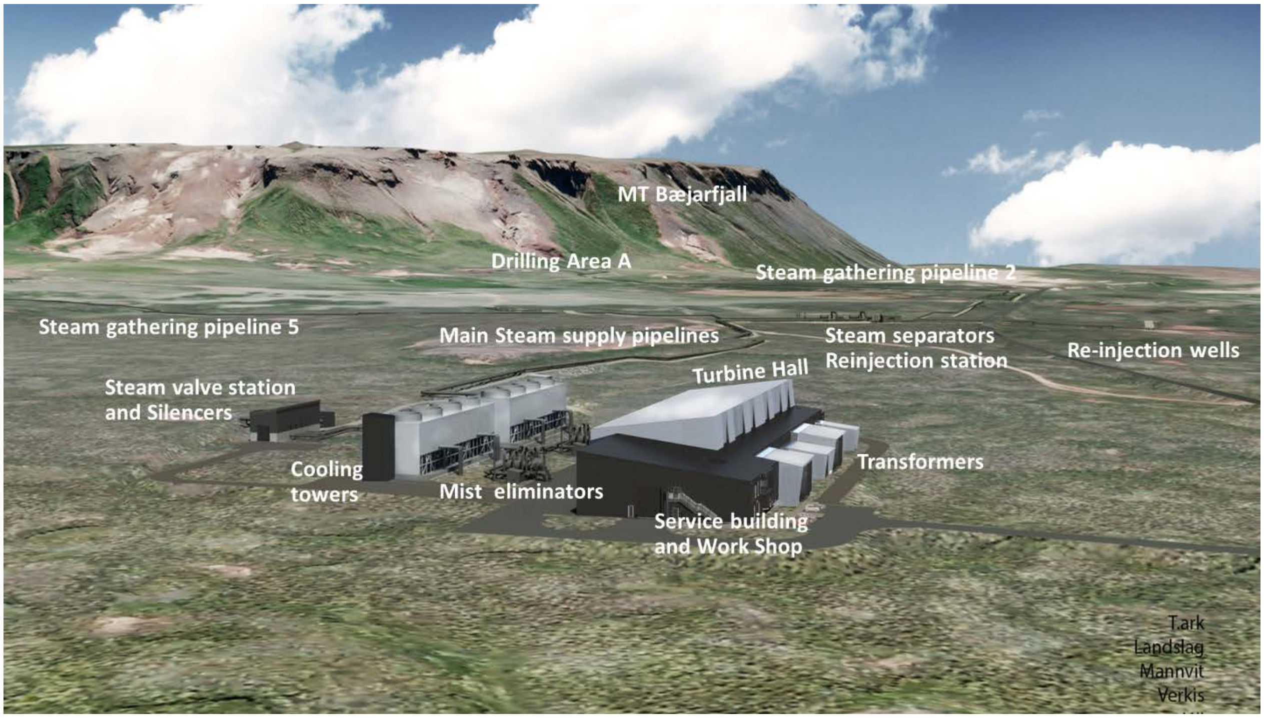

Figure 2: Overview of the power plant, showing the power house, consisting of turbine hall, service building and workshop, cooling towers and buildings and equipment of the steam supply.

2.1 Steam supply

The steam supply is comprised of the steam wells, steam gathering pipelines, steam separators, steam pipelines, steam control valves, mist eliminators, reinjection pipeline and reinjection wells.

The steam wells are located on five drilling areas from where most of the wells are directionally drilled, a total of 17 wells. The average length of the wells is 2 500 m and their vertical depth ranges from 1 800 – 2 400 meters. The estimated power capacity of all drilled wells is 105 MWe. There are currently 13 geothermal wells connected to the steam supply and 10 in use, each well producing steam equivalent to 5-21 MWe of electrical power. The gas content of the steam is 0.21% by mass.

The two-phase fluid from the wells is piped to two steam separators, one for each turbine, where the steam is separated from the water. The steam is piped to the power house area and through mist eliminators to the turbines. Steam control valves, located in the steam valve station, are connected to the steam pipelines and vent the steam to steam silencers. The water from the steam separators is reinjected into wells at a depth of approximately 400 meters at the boundary of the geothermal field. To increase the permeability of the wells and reduce scaling, the geothermal water from the steam separators is mixed with condensate from the condensers of the turbines to cool and dilute the water, see Sigfússon and Gunnarsson (2011) and Gunnarsson (2011). An emergency exhaust for the water is connected to the reinjection line next to the reinjection wells.

The operation of the steam supply must facilitate the operation of the units at variable load and handle abrupt changes in the power output of the turbine/generator units without any delay in the operation of the units due to instability or transient behavior of the steam supply system. The two main control functions, thereby the main potential sources of instability, are the control of the steam pressure and the control of the level in the steam separators. The systems are coupled in the way that changes in steam pressure will affect the level in the separators.

The steam supply is operated with the wells at fixed opening. Controlled throttling of the wells is not deemed practical as rapid changes would strain the casing that will lead to failure and slower adaption to steam usage would limit the ability of the plant to rapidly adjust to load conditions. The pressure of the steam supply is controlled by the steam control valves by venting the steam to steam silencers. When the turbines are running at full or partial load, excess steam is vented to the steam silencers. If the turbines trip or are not in operation, all steam is vented to the steam silencers. In case there is not enough steam for operation at full capacity, one of the turbines will switch over to steam pressure control to maintain pressure in the steam supply.

The level in the steam separators is controlled by control valves on the reinjection wells that control the flow in the reinjection line. In addition to the flow of water from the geothermal wells, the level control in the steam separators is affected by the amount of condensate from the condenser being mixed in the reinjection line. The flow of condensate to the reinjection is controlled by the temperature of the mixed fluid, which is equivalent with control of mixing ratio of the fluids, currently the mixing ratio is 50/50. Control function in the condensate system of each unit prevents that the steam supply is not trying take too much condensate. In case the turbines trip, mixing of condensate will abruptly stop and disturb the level in the separators.

2.2 Turbine/Generator Units

The turbine/generator units consist of single flow turbine of the axial exhaust type, generator and terminal equipment, condenser, gas extraction system and cooling water circuit with wet cooling tower. The design, manufacturing, installation and commissioning was done by the consortium of Fuji Electric and Balcke-Dürr. All equipment of the turbine/generator unit are located within the turbine hall of the power house, except for the cooling tower, see Figure 3.

The turbine design is single cylinder condensing with twelve reaction type stages. The turbines have a rated output of 45 MW_e each and maximum output of 47.25 MW_e. The design inlet pressure of the turbine is 9.0 bar_a and condensing pressure 0.08 bar_a, allowable inlet pressure range is 6.5 to 10.5 bar_a. The generator is directly shaft coupled to the turbine. The generator is rated 50 MVA, at 11 kV and 50 Hz. The excitation system is a brushless type.

The condenser is of shell and tube type. The steam condensate in the condenser is pumped out to the condensate circuit from where the condensate is led to booster pumps that pump the condensate to the reinjection pipeline in the steam supply where it is mixed with the geothermal water. The condensate can also be used as make-up water in the cooling water circuit

The cooling water circuit is used for the condenser, oil and generator coolers, the intercondenser of the gas extraction system and the gland steam condenser. The cooling tower is of the mechanical induced draught wet type and counter flow. The cooling towers consists of three cells, each with two-speed fan. The make-up water for the cooling water circuit is mainly with cold water from the water supply but condensate from the condenser is also being used.

The gas extraction system extracts the noncondensable gases from the condensers and consist of four identical systems. The system is hybrid, where the first step is by steam ejector with intercondenser and the second step is with a liquid ring vacuum pump. The total capacity of the gas extraction system is for gas content 0.6% by mass of the steam.

Figure 3: Turbine/generator units. Unit 2 in the foreground and unit 1 in the background.

2.3 Water Supply

The plant has its own ground water supply, located approximately 5 km from the power house, providing 8°C water. The current capacity of the water supply is 240 l/s but the pipeline allows for increase up to 370 l/s with additional pumps. The main usage of the water is make-up water for the cooling water circuits of turbine/generator units, but it also provides direct cooling water for the transformers, compressors for instrument air and seal water of the liquid ring vacuum pumps in the gas extraction system, as well as HVAC systems.

As a backup, a secondary water supply is located close by the powerhouse. The water supply was used during construction period, mainly to provide drilling water. The close vicinity to the geothermal field results in that the water temperature is around 26°C which limits its use as cooling water for direct cooling, but tests have shown that the units are able to operate with the backup water.

3. Special considerations due to a weak electrical grid and location of the plant

Geothermal power plants in Iceland are traditionally run as base load whereas hydro plants handle fluctuations in grid load. The majority of the geothermal power plants are located in the South-Western part of Iceland, in an area with a relatively strong grid and larger hydro units, e.g. Hallgrímsdóttir et al. (2012). Theistareykir Power Plant is, however, located in the North-Eastern part of Iceland where it will provide base load for the industrial area at Húsavík and the surplus energy goes to the ring connection of the grid. As the North-Eastern part of the transmission system is weak, the plant has additional requirements to enable responsive regulation during grid disturbances, appropriate to the location of the disturbance. The plant must be able to respond quickly in cases of nearby disturbances, e.g. trip of the industry load or trip of a transmission line. On the other hand, if the disturbance occurs further away, e.g. in the South-West part, the plant should avoid responding to avoid overloading the weak ring connection.

The industry area is the largest consumer of electricity in the area and the silicon smelter located there is characterized by relatively large power intensive units. Any changes in power consumption, such as powering up/shutting down or any mishaps and outages, will have a large effect on the stability of the transmission system and create fluctuations in the frequency and voltage of the grid. Furthermore, transmission system failures, such as line faults in severe weathers or instabilities in the grid caused by events in other areas of the grid, can create situations where the plant is islanded and is required to actively control the frequency in the formed island, either on its own or with other power plants in the area, depending on the extent of the island.

Maintaining electricity to the industry area is essential to avoid production losses and any prolonged power outages may cause damages to the equipment of the consumer. Therefore, means for quick recovery are necessary in case the plant goes off the grid.

3.1 The transmission system in Iceland

The Icelandic transmission system consists of three 220 kV systems which are weakly coupled together with an outdated 132 kV ring connection, see Figure 4. For the last decade the installed capacity of the system has more than doubled, but in the meanwhile Landsnet (Icelandic transmission system operator) has not been able to reinforce the connection between these centers of generation and consumption. The transmission system is often submitted to large and rapid frequency excursions, mainly because of trips of its large power-intensive loads relative to the system size, unforeseen events in larger power plants connected to the grid or disturbances in the transmission system itself. Such events can overload the 132 kV ring connection, which occasionally result in system-split and islanding operation with increased risk of cascading events. Another issue with the weak coupling between the areas are power-oscillations between the West and East which occasionally become unstable and cause islanding events. The issues mentioned above makes operating the grid a challenge and calls for fast responses, with automated and coordinated controls to secure the stability and reliability of the power system.

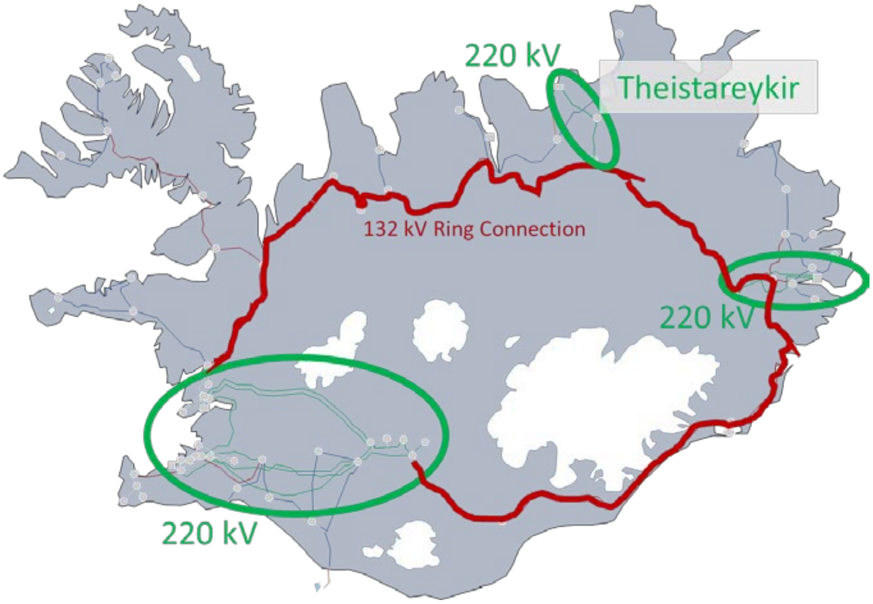

Figure 4: Overview of the transmission system for electricity in Iceland. Theistareykir is located in the North-East of Iceland with a 220 kV connection to the industrial area at Húsavík and to the 132 kV ring connection.

3.2 Special measures in a weak grid with low inertia

The requirements made at the design stage of the power plant to counter eventual unforeseen events in the power system involve mainly the design of the governor of the turbine and the automatic voltage regulation system. The requirements focus on functions to maintain stability of the grid but also functions to minimize disruption in the operation of the units and minimize down time.

The governor has been implemented with several functions that enables the unit to respond to unforeseen events. The load controller is supplemented with a droop function to contribute to frequency regulation for smaller frequency variations. The units switch to frequency control and actively participate in the control of the grid frequency when frequency fluctuations go beyond certain limits set in the governor. If the plant is islanded only with the industrial area, the units will solely control the frequency in the island. Frequency control can also be initiated by an external signal in a special Island mode where one unit switches directly to frequency control whereas the other unit maintains load control with power setpoint. The governor is also equipped with fast load reduction function that lowers the power output to minimum continuous load, initiated in case of over generation in the grid.

In case the units disconnect from the grid, measures have been implemented to minimize the down time. In case the electrical protection opens the generator circuit breaker and trips the unit, the control system has been implemented with an automatic start up sequence that can be initiated and speeds the turbine up again for resynchronization. In case the substation circuit breaker opens, the requirement is that the turbine goes to house load, i.e. the turbine switches to frequency control, and maintains power on the power plant, thereby minimizing disruption in operation of the units, supply systems, auxiliary systems and ancillary systems.

Power system stabilizers (PSS) have been installed, to provide a supplementary control signal to the voltage regulator to improve dynamic stability of the generator during transient events. The stabilizer derives the signal from the change in power output and allows the units to participate in stabilizing oscillations in the grid.

In case of a complete black out of the power plant and the transmission line, the units have been provided with black start capabilities using a diesel generator that allows for starting up the turbine, energizing the transformers and the transmission lines.

3.3 Special measures due to location

Although the Theistareykir power plant is only about 20 minutes’ drive from the town of Húsavík, the elevation of the plant and the weather conditions can make it difficult to reach the plant, especially during winter time. The plant will have minimum personnel on site with support from personnel at the Krafla Power Plant. In case operators are needed at the plant, there is a 40-60 minutes’ drive to Theistareykir from Krafla, depending on conditions.

An effort has been made to incorporate automation to facilitate remote operation. An operator console for Theistareykir Power Plant is located at the Krafla Power Plant which allows operators to monitor and intervene if necessary. For instance, automatic start-up/shut-down sequences have been implemented for the units which allows operation of the unit to minimize intervention needed by operators. It is expected that the majority of the incidents that need an operator’s attention will be due to grid instability where in most cases it is possible to immediately resynchronize the units, which the operators would be able to do remotely.

The design of the plant has incorporated sufficient redundancy to guarantee that a single failure will not affect the power production and minimize the need for immediate operator intervention on location. An effort has been made to ensure that all functions implemented allow the plant systems to recover automatically from faults as much as possible.

4. Performance of the plant

Landsvirkjun and Landsnet have performed various system tests to verify the response and the resilience of the power plant in the weakly connected grid. The power system stabilizers (PSS) of the units have been tuned and commissioned. It has been verified that the units are providing positive damping of the most critical frequency bands and there is a reduced risk of unstable power oscillations within the North-East area and between the main centers of power production in the South-Western and Eastern part of Iceland. The regulation capabilities of the units have also been thoroughly tested and the results show that the geothermal units are technically capable of providing fast and responsive regulation. The performance of the plant’s supply systems has been tested and their response to disturbance events have been proven reliable.

4.1 Islanding event

Islanding events can be comprised of different splits depending on the source of the instability in the grid. Theistareykir Power Plant can for example be in an island with other power plants in the Northern and/or Eastern part or alone with the industry area at Húsavík. Figure 5 shows test results of an islanding split where Theistareykir forms a small island with the power intensive industry area at Húsavík, at that time there was not a significant power usage at the industry area and the power from the plant was going to the ring connection. The 220 kV transmission line from the substation at Krafla Power Plant, was manually opened where it connects to the ring connection with 60 MW_e of surplus generation in the island formed by Theistareykir Power Plant and the industry area. The units responded by reducing their production from 30 MW_e down to 1 MW_e in only 1 second (turbine opening position can be seen on Figure 4) and were able to limit the frequency rise due to overgeneration within 51 Hz. Furthermore, the units were able to stabilize the voltage within the island, the voltage went above the +10% limit from the nominal voltage level only for a short time. This test demonstrated the capability of the units to rapidly respond to an islanding event and their ability to regulate the islanded system without tripping, which would have resulted in a blackout of the island. The response time of the units is significantly faster than a similarly sized hydro power plant unit.

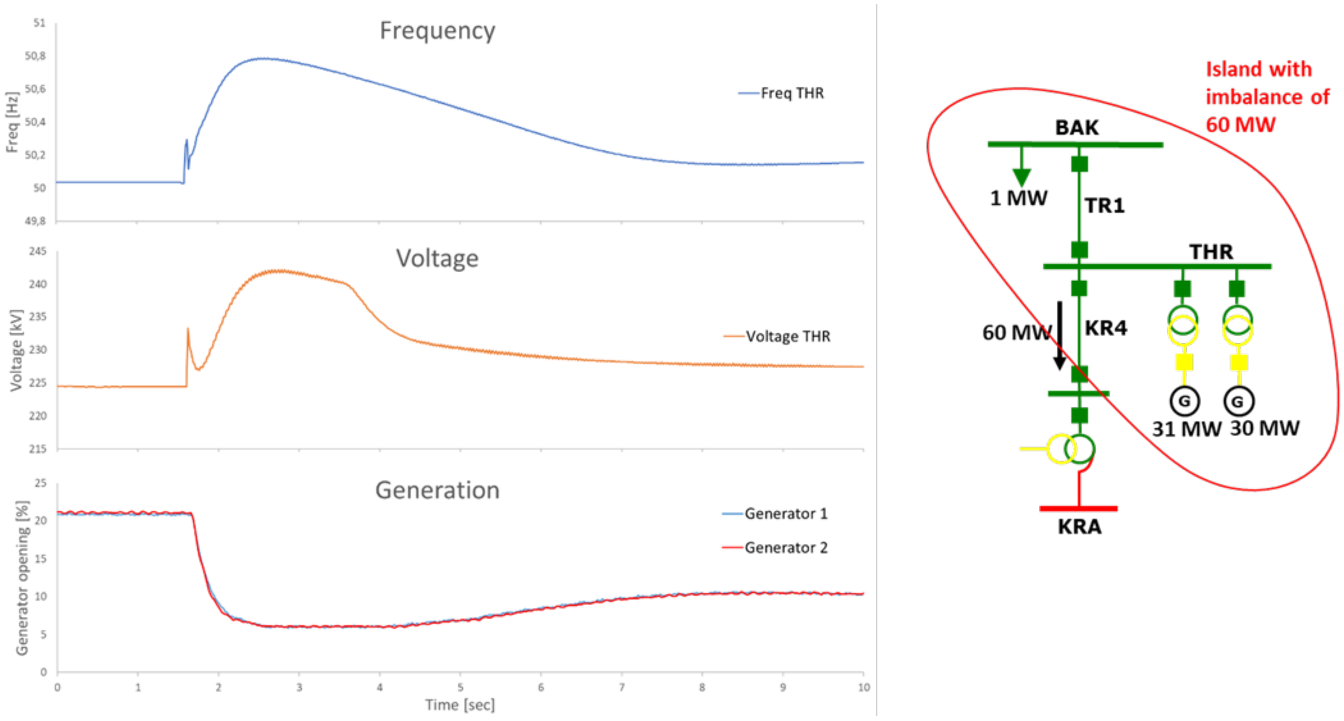

Figure 5: System response in an islanding event with 60 MW_e surplus of generation when circuit breaker of transmission line KR4 at Krafla substation (KRA) is opened, leaving the power plant (THR) and the industry area (BAK) in an island

4.2 Response to frequency deviations

During the commissioning period of Theistareykir power plant the frequency regulation was tested during real events in the transmission system by the deliberate opening of network switches, leaving Theistareykir in an island with larger hydro units in the Eastern part. The normal mode of the governor is load control with a power setpoint as the units are run as baseload but if deviations in frequency exceed certain set limits, the governor switches automatically to frequency control mode.

Figure 6 shows a high frequency event and how different governor control modes performed in the event, load control and frequency control, where the switching to frequency control mode was disabled on one of the units. During the test, the limits for switching to frequency control mode are triggered if frequency deviation exceeds ±1.0 Hz or if the frequency deviation exceeds ±0.7 Hz and the rate of change of frequency exceeds ±0.3 Hz/s.

Figure 6 shows that as the frequency event occurs, the load output of the units is disturbed and starts to oscillate slightly while the units are still in load control but with the droop active. Once the frequency deviation and rate of frequency change limits triggers the switch to frequency control mode, the governor of that unit starts to actively regulate the grid frequency by lowering its load output, thereby contributing to stabilizing the grid frequency along with the other units on the grid. The regulation speed of the unit was about 18 MW/s which is much faster than hydro units are able to perform. Figure 6 shows clear advantages of letting the unit switch to frequency mode instead of maintaining load control mode.

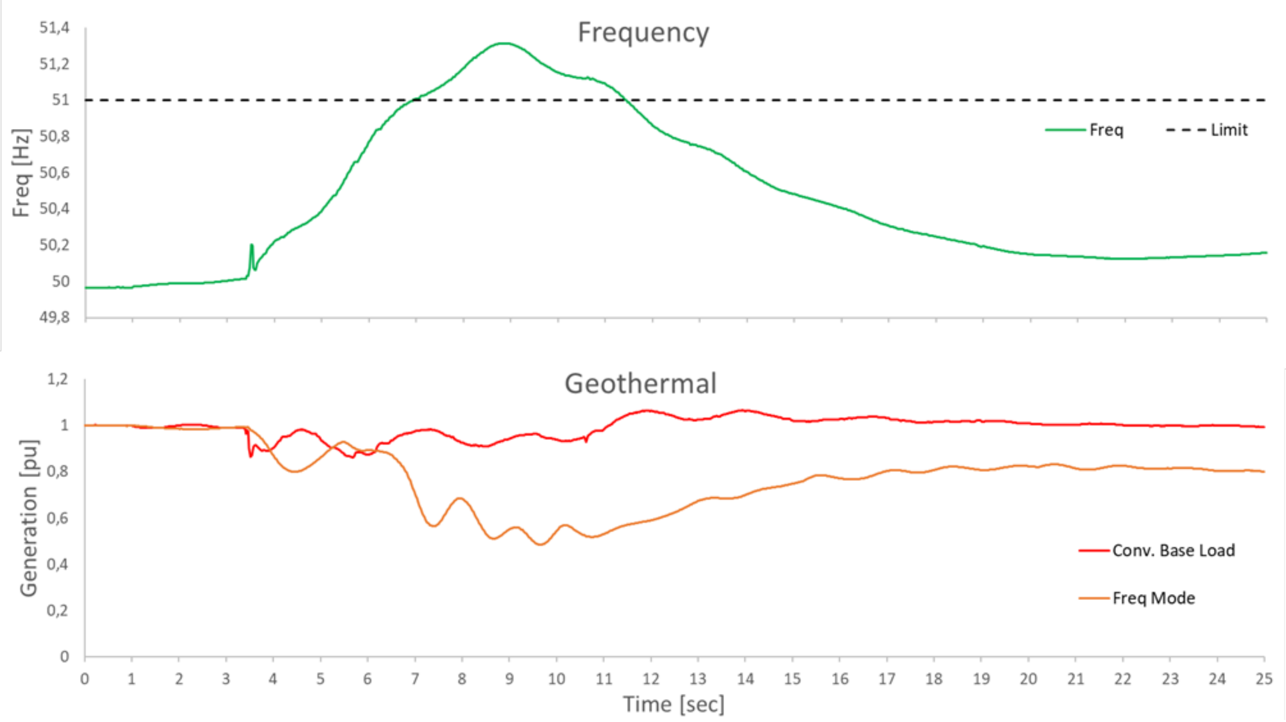

Figure 6: Response of the units to an unforeseen over frequency event. One unit maintain load control mode whereas the other switches to frequency control mode when the +0.7 Hz and 0.3 Hz/s limit is reached.

The test also highlights the need for a more intelligent control of the switching to frequency control mode. In this case it would have been more beneficial if the triggering to frequency control had been sooner. However, if the units are too sensitive, the units will switch over to frequency control mode when it is not necessary. For example, if the disturbance is happening in another part of the grid, the switch to frequency control of the units will introduce unnecessary stress on the ring connection and potentially cause an unwanted islanding event. Intelligent control of Theistareykir is currently under development, utilizing Wide-Area-Controls, with the aim to evaluate and trigger effective regulation performance of the units under the right circumstances, see Wilson and Heimisson (2018) for further details. The intelligent controller would immediately give external signals to change over to frequency control mode in case of islanding or other unexpected events in North-East. On the other hand, inhibit the units to switch over to frequency control mode if the disturbance is happening in another part of the grid.

4.3 Load rejection

During the commissioning of the industrial area, an event occurred where both substation breakers opened due to overcurrent when both units were at full capacity, see Figure 7. The response of the units resulted in load shedding of unit 1 and it went to house load, producing 3.4 MW_e for the plant's parasitical load, whereas unit 2 went to no load, maintaining 3000 rpm and ready to synchronize. Both units were therefore immediately ready to resynchronize to the grid as soon as grid conditions would permit. In this event, down time of the units was 35 minutes while the causes for the mishap were investigated, however, in other disturbance events, a unit has been resynchronized within 15 minutes after the trip of the unit.

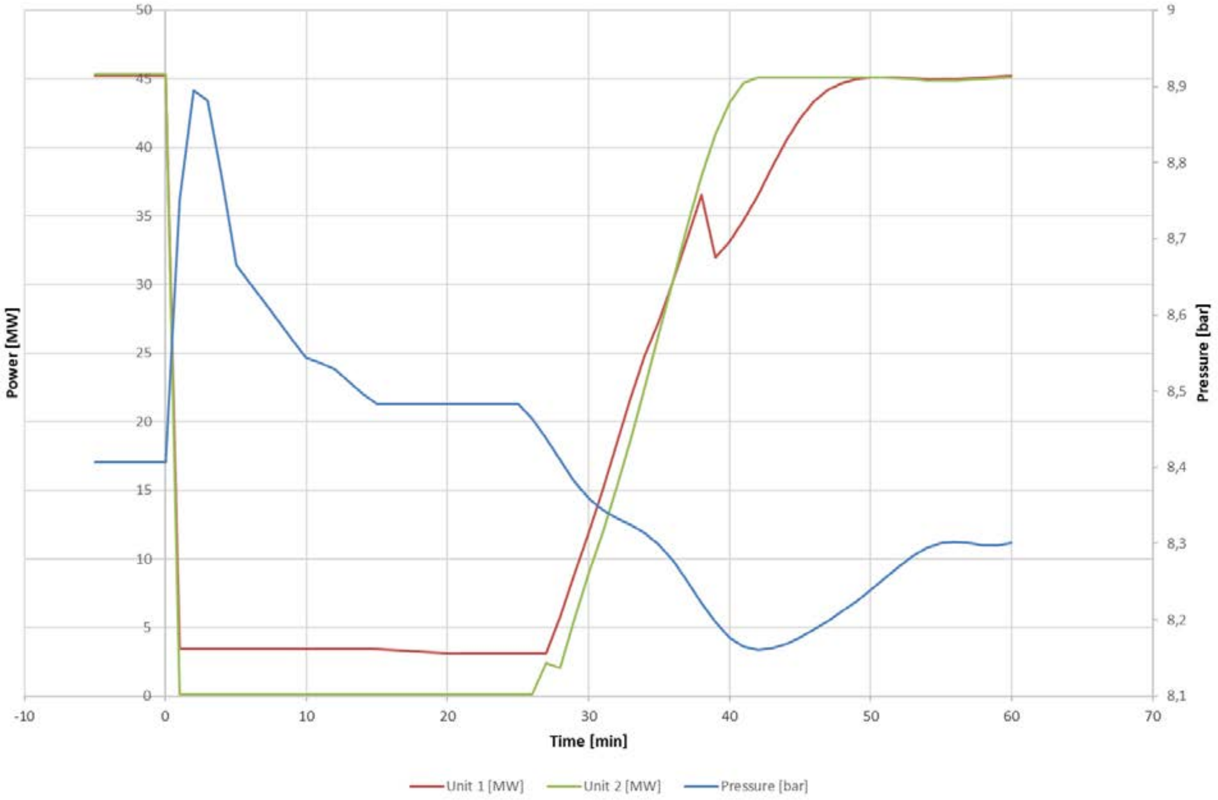

Figure 7: Load rejection with both units at full load. Unit 1 switches to house load, producing 3.4 MW_e (left axis), whereas unit 2 is in no load until the units are resynchronized and set to full load again. Steam pressure is initially 8.4 bar and peaks at 8.9 bar following the load rejection (right axis)

Simultaneous load rejection of both units is one of the most severe tests for the stability of the steam supply, after full trip of both units. As both units are at full load, all steam control valves are closed, except one that is bleeding off excess steam. The steam control valves must open and exhaust almost all the steam to the silencers to maintain steam pressure within limits. The reinjection system must react to the disturbance in the level of the steam separators due to the rise of steam pressure and an abrupt change in the amount of water to the reinjection wells as the loss of condensate from the units reduces the flow in the reinjection line by more than a half.

Figure 7 shows the steam pressure in the steam supply and how the steam control valves limit the pressure rise within 8.9 bar peak rise from initial 8.4 bar and stabilize the pressure at 8.5 bar. The reinjection was further able to stabilize the level in the separators in a smooth manner without any destabilizing effects on the steam supply. It can be further noted in Figure 6 that as both units are resynchronized and start to load up, the steam pressure drops while the steam control valves are closing. That triggers unit 1 to switch briefly to steam pressure control and assist in maintaining steam pressure. As the pressure stabilizes, the unit switches back to load control and goes to full load.

6. Conclusions

Landsvirkjun’s Theistareykir Power Plant has been successfully put in operation with set objectives achieved in good cooperation with Landsnet (transmission system operator) and the consortium of Fuji Electric and Balcke-Dürr (contractor for the units). The power plant is connected to a weak, low inertia, grid in the North-Eastern part of Iceland and provides baseload power production. However, due to its location and grid characteristics, Theistareykir Power Plant has requirements to be able provide responsive regulation during grid disturbances and islanding events.

The performance of the units and the supply systems in handling unexpected events during testing has shown to be beneficial for the grid stability. In particular, the results show the ability of the units at Theistareykir Power Plant to participate actively in regulating the grid frequency. The response time of the units is significantly faster than a similar sized hydro power plant and the tests have proven that the units are capable of rapidly adapting to changes and able to contribute to the stability of the transmission system. Results on tests for an islanding event, frequency disturbances and load rejection were reported.

Geothermal power plants have the potential to contribute significantly to improve the stability and flexibility of Iceland’s power system and complement the response of the hydro power plants. Landsvirkjun and Landsnet are currently working together to design of an intelligent controller for Theistareykir Power Plant. The design will utilize both local controls and Wide-Area-Controls from Landsnet’s PMUs (Phasor Measurement Units) / WAMS (Wide-Area-Measurement-System), which is essential tool to identify in real time the location and severity of unforeseen events in the power grid. With the intelligent controller, the ability of Theistareykir Power Plant to contribute to the stability of the transmission system will be further improved.

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