Dynamic Behavior of Geothermal Power Plants Located at a Weak Point of a Transmission System

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I was born in Reykjavik Iceland in 1980.

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This thesis is submitted to fulfill the requirements for the M.S. degree. The preparation began in the fall of 2007 and the simulations were done in spring 2008. All the data was provided by Landsnet, the Icelandic transmission company. The advisor, Professor de León of Polytechnic University, was immensely supportive throughout the project and was vital in providing knowledge and focus on the most important theoretical and engineering issues.
AN ABSTRACT

Dynamic Behavior of Geothermal Plants Located at a Weak Point of a Transmission System

by

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Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science (Electrical Engineering)

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In recent years, predictions of increasing global climate change have sparked interest in the use of geothermal energy. In addition to limiting countries’ fossil fuel dependence, studies have shown up to 35-fold reduction of CO₂ emissions when compared to the use of coal. In Iceland, 77% of power generation in 2008 is hydropower and the rest comes from geothermal energy. Iceland’s power companies plan to build numerous geothermal plants in coming years thus increasing the proportion of geothermal energy of the total generated energy.

The objective of this thesis is to give answers to the following questions:

❖ What will happen when a group of geothermal plants are connected to the transmission grid at a weak point of the system?
❖ What is the difference in the power system stability when a large power demand is met with hydro power plants vs. geothermal plants?
❖ When planning a new aluminum smelter in northern Iceland, looking at the voltage stability, with the N-1 criteria in mind, which reinforcements are needed to connect the load and the new plants to the transmission system?

To answer the questions three studies were carried out: (1) Transient stability, where the critical clearing time of an important line is compared when the nearby generation is hydro versus geothermal. (2) Voltage stability for the N-1 contingency was used to determine the transmission expansion. (3) A switching transient consisting of a single pole opening and reclosing to determine the over-currents and over-voltages. While for the first two studies the entire system was considered, for the latter the systems was reduced to the terminals of the line.

The answers to the questions found during the development of the thesis are:

❖ The geothermal power plants to be installed have larger inertia than the power hydro plants they substitute. Therefore, the system is more likely to maintain stability under transient condition when the load is supplied from geothermal plants.
❖ When a large power demand is met with only geothermal power plants the system will be more stable than if it is met with hydro plants.
❖ When planning a new 250 MW aluminum smelter in northern Iceland where the power demand is met with both geothermal and hydro power plants we used a voltage stability study to determine the reinforcements needed to connect the load and the new plants to the transmission system.
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1 Introduction

1.1 Motivation
In recent years, predictions of increasing global climate change have sparked interest in the use of geothermal energy. In addition to limiting countries’ fossil fuel dependence, studies [1] have shown up to 35-fold reduction of CO$_2$ emissions when compared to the use of coal.

Iceland is one of the main geothermal energy users worldwide. The geothermal energy is used both for space (house) heating and to generate power. Potential sources of clean energy are abundant, both geothermal energy and hydropower.

In Iceland, 77% of power generation in 2008 is hydropower and the rest comes from geothermal energy [2]. Iceland’s power companies plan to build numerous geothermal plants in coming years thus increasing the proportion of geothermal energy of the total generated energy.

1.2 Objectives
When an increasing number of geothermal power plants are connected to the Icelandic transmission system, questions arise for transmission operators. The objective for this thesis is to find the answers for the following questions:

- What will happen when a group of geothermal plants are connected to the transmission grid at a weak point of the system?
- What is the difference in the power system stability when a large power demand is met with hydro power plants vs. geothermal plants?
- When planning a new aluminum smelter in northern Iceland, looking at the voltage stability, with the N-1 criteria in mind, which reinforcements are needed to connect the load and the new plants to the transmission system?

1.3 Scopes and Limitations
There are two main studies in this thesis: transient stability and voltage stability study. A reduced scope switching transient study is also presented.

In the transient stability study the aim is to compare the stability of a system where the power demand for a new load, located at a weak point of the transmission system, is met with geothermal plants or with hydro plants. The comparison is made by determining the critical clearing time of the most influential fault.

The voltage stability study determines which reinforcements are needed when connecting a new load (located at the same place as for the transient stability study) where the power demand is met with combination of hydro and geothermal plants.

The switching transient study is a small study where the Icelandic transmission system is simplified and single pole switching and reclosing is used to determine the maximum overvoltage and overcurrent.

1.4 Literature Review
Published research on geothermal power plants is rare and parameters are not easily available. The research tends to be more focused on thermodynamics rather than on electrical properties.

There are no stability studies published comparing the stability performance of geothermal power plants with other generation technologies; however, the papers covered in section 1.4.1 contained valuable general information about geothermal power plants.

This led to a problem that essential parameters of the model were not available in published research and had to be gathered from internal documents of the Icelandic Transmission Company.
1.4.1 Papers

Geothermal Power Technology [3]
The paper has a review of power plants that mentions turbines in geothermal plants and has diagrams that show geothermal process and flow. It also mentions the efficiency of geothermal power turbines with (78%-83%) and (50%) without condenser. Geothermal turbines are usually made of the same alloys as low pressure turbines used in fossil-fired plants. Variations on the alloy composition of the blades and rotors enhance the alloy’s ability to withstand corrosion and stress corrosion cracking. The combined effect of the limited blade length and the reduced flow rate per unit area limit the maximum size that can be achieved in a geothermal turbine-generator; thus, it is common to see three 55 MW_e units installed in a single power house rather than a single 165 MW_e unit.

Discusses how to model and simulate a geothermal power plant. Gives some general equations with little detail and includes good descriptions of different parts of the plant.

Simulations and Performance Analysis of the New Geothermal Co-Generation Power Plant (OV-5) at Svartsengi [5]
Comparison of the model’s and manufacturer’s results shows that the static and dynamic behavior of the power plant at different electrical and heat loads can be analyzed by the simulations.

In this research, a geothermal power generation model was constructed based on the characteristics of the steam well, and the generation of electricity was estimated precisely by the constructed model. The model is based on a standard mathematical model where the inputs are the steam pressure and flow rate and the output is production of electricity. The complicated physical phenomena involved can be simplified by the equivalent turbine model. The proposed model is used not only for rated operation but also for arbitrary conditions of operation. Derivation of turbine equivalent model is in the appendix.

The paper’s interest is predicting the performance of energy systems in all operating conditions which is one of the most important issues for reducing investment cost and optimizing system efficiency. Simulation code for design and off design behavior of two Italian 20 MW and 60 MW geothermal power plants are developed and tested with experimental data of the plants. The influence of the geothermal fluid main characteristics is also studied.

Model of combined-cycle power plant was developed to predict its transient behavior. The transients, driven by step and sinusoidal variation in the gas turbine load, are included. The paper shows that thermal inertia of the steam cycle is larger than of gas turbine cycle. Steam cycle response has a time lag and shows a damping effect on the variation of the turbine load. Also, when the periodic disturbance is imposed to the gas turbine and the time scale of the disturbance is quite less than the characteristic time scales of steam cycle, the effect of the disturbance on the steam cycle is negligibly small.

1.4.2 Books
Not many books cover the specific topic of this thesis; however, the following books had valuable information about stability and are highly recommended:

- Power System Stability and Control by P. Kundur
- Power System Control and Stability by P.M. Anderson and A.A. Fouad
- Power System Analysis by J.J. Grainger and W.D. Stevenson
- Power System Analysis, 2nd ed. by H. Saadat
Difference between Generation Technologies

2.1 Thermal Power Plants

In thermal power plants, mechanical power is produced by transforming thermal energy, often from combustion of a fuel, into rotational energy. The most common source of combustible fuel is fossil fuel: coal, oil and natural gases. The fuel is burned in boilers where the heat is used to convert water into steam. The steam drives turbines that drive power generators. A layout of a thermal power plant that uses coal as fuel can be seen in Figure 1.

Figure 1: Layout of a thermal power plant that uses coal as fuel [9].

Other sources of thermal energy are nuclear reactor’s heat, geothermal heat and heat produced in renewable energy plants that may be fuelled by municipal solid waste, waste from sugar cane and landfill methane or other forms of biomass [10].

There are three main types of prime movers: steam turbine, gas turbine and combined cycle.

2.1.1 Steam Turbines

Steam turbines use the dynamic pressure of the steam to turn the blades of the turbine, as explained above. Almost all large non-hydro plants use this system [10].

2.1.2 Gas Turbines

Gas turbines use the dynamic pressure from flowing gases to directly operate the turbine. Natural-gas fuelled turbine plants can start rapidly and so are used to supply “peak” energy during periods of high demand, though at higher cost than base-loaded plants [10].

2.1.3 Combined Cycle Power Generation

Combined cycle power generation is a method of generating electric power that combines gas turbine power generation with steam turbine power generation. The combined cycle layout is illustrated in Figure 2. The gas turbine is fired by natural gas and the steam boiler and steam turbine use the exhaust gas from the gas turbine. This greatly increases the overall efficiency of the plant and can be easily engaged and disengaged in a short period of time, making it possible to cope with changing power demands.
Higher efficiency and capacity can be achieved by raising the inlet gas temperature of the gas turbine.

2.1.4 Cooling Towers

Because of the fundamental limits to thermodynamic efficiency of any heat engine, all thermal power plants produce waste heat as a byproduct of the useful electrical energy produced. Natural draft wet cooling towers at nuclear power plants and at some large thermal power plants are large hyperbolic chimney-like structures that release the waste heat to the ambient atmosphere by the evaporation of water.

Where economically and environmentally possible, it is preferred to use cooling water from the lake, river or ocean instead of a cooling tower. It can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through the plant's heat exchangers. However, the waste heat can cause the temperature of the water to rise detectably. Power plants using natural bodies of water for cooling must be designed to prevent intake of organisms into the cooling cycle. Another environmental effect can be organisms that adapt to the warmer plant water and may be injured if the plant shuts down in cold weather [10].
2.2 Hydro Power Plants

There are three types of hydropower facilities: impoundment, diversion, and pumped storage.

Impoundment
The most common type of hydroelectric power plant is an impoundment facility, sometimes called high-head plant. A layout of a high head plant can be seen in Figure 3. An impoundment facility, typically a large hydropower system uses the potential energy of dammed water driving a water turbine and generator. The height difference is called the head and the amount of electricity that is generated depends on the head and the volume [12], [13].

Diversion
A run-of-the-river plant has no reservoir. They rely on the flow of a river or waves and tides of the sea to spin the turbines. These plants produce a much smaller amount of electricity than other hydropower facilities [13], [14].

Pumped Storage
Pumped storage hydro plants are used to supply high peak demands. Water is pumped from a lower reservoir to an upper reservoir at times of low electrical demand and then at peak demand it flows through the turbine back to the lower reservoir [12], [13].

There are two main types of hydro turbines: impulse and reaction. The type of hydropower turbine is selected when a project’s operational studies and cost estimates are completed, and is based on the height of the head, flow and/or volume of water. Other deciding factors include how deep the turbine must be set, efficiency, and cost [12], [15].

2.2.1 Impulse Turbine
The impulse turbine can be either horizontal or vertical and uses the kinetic energy of water striking its runners buckets or blades to cause rotation. The water flows in the turbine, hitting each bucket causing the runner to turn and then flows out the bottom of the turbine housing. An impulse turbine is generally suitable for high head, low flow applications [12], [15].

2.2.1.1 Pelton
A Pelton wheel is a horizontal impulse turbine. It has one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Impulse turbines do not require draft tubes since the runner must be located above the maximum tailwater to permit operation at atmospheric pressure [12].

One variation of the Pelton wheel is a Turgo wheel but its runner is a cast wheel whose shape generally resembles a fan blade that is closed on the outer edges. The stream of water is applied to one side, it goes across the blades and then exits on the other side [12].

2.2.1.2 Cross-Flow
A Cross-flow turbine is a drum-shaped impulse turbine that uses an elongated, rectangular-section nozzle directed against curved vanes on a cylindrically shaped runner. It was developed to accommodate larger water flows and lower heads than the Pelton. The Cross-flow allows the water to flow the blades twice; the first pass is when the water flows from the outside of the blades to the inside and the second pass is from the inside back out [12].
2.2.2 Reaction Turbine
A reaction turbine is a horizontal or vertical wheel that develops power from the combined action of pressure and moving water. Unlike the impulse turbines, the runner is placed directly in the water stream, so the water flows over the blades instead of hitting each bucket. Reaction turbines are used for lower head and higher flows and are the type most widely used [12], [15].

2.2.2.1 Propeller
The Propeller’s turbine runner has usually three to six blades in which the water contacts all of the blades constantly. Other major components of the Propeller turbine besides the runner are a scroll case, wicket gates, and a draft tube [12]. According to [12] there are four types of propeller turbines:

- **Bulb turbine**: The turbine and generator form a sealed unit that is placed directly in the water stream.
- **Straflo**: The generator is attached directly to the turbine’s perimeter.
- **Tube turbine**: The penstock is bent just before and after the runner, allowing a straight line connection to the generator.
- **Kaplan**: Both the blades and the wicket gates are adjustable so a wider range of operation is possible.

2.2.2.2 Francis
The Francis turbine has a runner with usually nine or more fixed buckets. The water is introduced just above the runner and all around it and then falls through, causing it to spin. Other major components besides the runner are the scroll case, wicket gates, and draft tube [12].

2.2.2.3 Kinetic
The Kinetic energy turbine, sometimes called the Free-flow turbine, generates electricity from the kinetic energy present in flowing water instead of using the potential energy from the head. These turbines are used in rivers, man-made channels, tidal waters, and ocean currents using the water stream’s natural pathway. Kinetic systems do not require the diversion of water through man-made channels, riverbeds, or pipes, although they might have applications in such conduits. These systems can use existing structures such as bridges, tailraces, and channels but they do not require large civil works [12].
2.3 Geothermal Power Generation

Instead of using fossil fuel to generate the steam, geothermal (hydrothermal) fluids can be used to generate electricity. The type of conversion used depends on the state of the fluid, steam or water, and its temperature. There are mainly three conversion technologies used, dry steam, flash and binary cycle.

2.3.1 Dry Steam Power Plants

Steam power plants use geothermal fluids that are primarily steam to drive the turbine which drives the generator. This is the oldest type of geothermal power plant and was first used in Larderello Italy in 1904 and is still very effective. Layout of this type of plant can be seen in Figure 4. These plants emit only excess steam and very minor amounts of gases [16].

![Dry Steam Power Plant](image)

Figure 4: Dry steam power plant [17].

2.3.2 Flash Steam Power Plants

Geothermal fluids that are above 200°C/400°F can be used in flash plants. The fluid from the production well goes into a tank that is held at a very low pressure so when the fluid comes to the surface under a falling pressure it flashes into steam [16]. Plants of this type are called single flash and the layout can be seen in Figure 5.

![Flash Steam Power Plant](image)

Figure 5: Single flash power plant [17].
In double flash plants, two flashers occur and are therefore more efficient. One below the surface as in single flash plants and one above the surface in specially designed flash tank. In the second stage the liquid that remains in after the first stage is flashed again and therefore captures a portion of the energy otherwise wasted. Only excess steam and trace gases are emitted. Plants of this type are operating in Iceland (Krafla) and in Japan (Hatchobaru) [16], [18].

A multishift plant employs steam at three of more levels of pressure at turbine entry points.

### 2.3.3 Binary-Cycle Power Plants

Binary-Cycle power plants use moderate-temperature water, less than 200°C/400°F that is by far the more common geothermal resource. The geothermal fluid heats a secondary (binary) fluid that has a much lower boiling point through a heat exchanger. The secondary fluid, typically a fluorocarbon or a hydrocarbon, flashes to steam and drives the turbine. Because this is a closed loop system, virtually nothing is emitted to the atmosphere [16], [18]. Layout of a binary-cycle power plant can be seen in Figure 6.

![Binary Cycle Power Plant](image)

**Figure 6: Binary-cycle power plant [17].**

### 2.4 Alternative Generation Methods

#### 2.4.1 Solar Generation

Solar power plants convert the energy from the sun to electricity by photovoltaics, concentrating solar thermal devices or various experimental technologies. There are mainly three technologies used:

##### 2.4.1.1 Solar Trough System

Most solar power plants use solar trough technology. These plants use parabolic shaped solar collectors and receiver pipes located on the collectors, see layout in Figure 7. Synthetic oil circulates through the pipes and captures the heat, reaching temperature as high as 390°C (735°F). Then the hot oil is pumped into a generating station and routed through a heat exchanger to produce steam and finally electricity is produced in a conventional steam turbine [19] [20].
2.4.1.2 Solar Power Towers

This type of technology is unique because it can store energy efficiently and cost effectively. They usually produce electricity on a large scale and can operate whenever the customer needs power, even at nights and during cloudy weather [19].

Solar power towers technology use thousands of flat sun-tracking mirrors called heliostats that are face a receiver that is located at the top of a centrally located tower. The intense energy concentrated onto the tower produces temperatures up to 1500°C (2732°F). The gained thermal energy is then used to heat salt or water which saves the energy for later used. That thermal energy is then used to generate steam for a conventional steam turbine [19] [21]. A layout of the solar power technology that uses salt for the heat exchange can be seen in Figure 8.

2.4.1.3 Solar Dish / Engine Systems

Solar dish or engine systems convert the energy from the sun into electricity at a very high efficiency. This technology uses a mirror array formed into the shape of a dish. The solar dish focuses the sun’s rays onto a receiver that transmits the energy to an engine, typically a kinematic engine that generates electric power [19].

Solar dishes are efficient at collecting solar energy at very high temperatures, because of the high concentration ratios achievable with parabolic dishes and the small size of the receiver. Tests of prototype systems and components have demonstrated net solar-to-electric conversion efficiencies as high as 30%, which is significantly higher than any other solar technology [19].
These systems can operate as stand-alone units in remote locations or be linked together in groups to provide utility-scale power [19].

2.4.2 Wind Generation

Wind is a form of solar energy because winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind turbines convert the kinetic energy in the wind into mechanical power that can be used for specific tasks such as grinding grain or pumping water or a generator can convert this mechanical power into electricity. The wind turns the blades, which spin a shaft that connects to a generator to produce electricity [22].

Modern wind turbines fall into two basic groups:

- the horizontal-axis variety
- the vertical-axis design

Horizontal-axis wind turbines typically either have two or three blades with the blades facing into the wind.

Wind turbines range in size from 100 kilowatts to as large as several megawatts. Larger turbines are grouped together into wind farms providing bulk power to the electrical grid. Smaller turbines, below 100 kilowatts, are used for homes, telecommunications dishes, or water pumping [22].

Typical wind turbine can be seen in Figure 9 and below is a description of each part from [22].

![Figure 9: The wind turbine [22.]](image)

- **Anemometer**: Measures the wind speed and transmits wind speed data to the controller.
- **Blades**: Wind blowing over the blades causes the blades to "lift" and rotate.
- **Brake**: A disc brake can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.
- **Controller**: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour and shuts off the machine at about 55 mph. If the wind speed is above 55 mph the turbine does not operate because they might be damaged by the high winds.
- **Gear box**: Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, which is the rotational speed required by most generators to produce electricity.
- **Generator**: The generator is usually an off-the-shelf induction generator that produces 60-cycle AC electricity.
- **High-speed shaft**: Drives the generator.
- **Low-speed shaft**: The rotor turns the low-speed shaft at about 30 to 60 rpm.
- **Nacelle**: Sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake.
**Pitch:** Blades are turned (pitched) out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too low to produce electricity.

**Rotor:** The rotor consists of the blades and the hub.

**Tower:** Made from tubular steel, concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

**Wind vane:** The wind vane measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

**Yaw drive:** The yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines do not require a yaw drive, the wind blows the rotor downwind.

**Yaw motor:** Yaw motor powers the yaw drive.

### 2.4.3 Nuclear Generation

Nuclear plants, like thermal plants, produce electricity by boiling water into steam that turns turbines to produce electricity. Instead of using fossil fuels or geothermal heat they use uranium fuel to produce the electricity through a process called fission that entails the splitting of atoms of uranium in a nuclear reactor. The uranium fuel consists of small, hard ceramic pellets that are packaged into long, vertical tubes and bundles of this fuel are inserted into the reactor [23].

There are two types of Uranium, U-238 and U-235, but most of the uranium in nuclear fuel is U-238. As the nuclei break up, they release neutrons. When these neutrons hit other uranium atoms, those atoms also split, they release neutrons of their own, along with heat. These neutrons then strike other atoms splitting them so each fission triggers others causing chain reaction so the fission becomes self-sustaining [23]. Control rods, inserted or withdrawn to various slow or accelerate the nuclear reaction.

The heat produced by fission turns water that separates the fuel tubes in the reactor into steam. The steam drives a turbine, which spins a generator to create electricity [23].

There are basically two types of Nuclear Power Plants

- boiling water reactors
- pressurized water reactors

Both types are cooled by ordinary water. The water is the main link in the process that converts fission energy to electrical energy. The boiling water reactors heat the water surrounding the nuclear fuel directly into steam in the reactor vessel and then the steam is carried directly to the turbine by pipes. Pressurized water reactors heat the water surrounding the nuclear fuel, but the water is kept under pressure to prevent it from boiling. The hot water is pumped from the reactor vessel to a steam generator where the heat from the water is transferred to a second separate supply of water. This water supply boils that produces steam to spin the turbine [23].
3 Power System Stability

Power system stability is the property of a power system to remain operating in equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after a disturbance [24].

Power system stability is a single problem that can take different forms and be influenced by a wide range of factors. Usually the stability is classified into three main categories:

- Rotor angle stability
- Voltage stability
- Mid-term & Long-term stability

3.1 Rotor Angle Stability

"Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor of the stability problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillate [24]."

The rotor angle stability is usually characterized in terms of two categories:

- Transient stability
- Small-signal stability

3.1.1 Transient Stability

Transient stability is the ability of the power system to maintain in synchronism when subjected to a severe transient disturbance, such as a fault on transmission facilities, loss of generation, sudden application or loss of a large load. The resulting system response to such disturbances involves large excursions of generator rotor angles, power flows, bus voltages, and other system variables. Transient stability is influenced by the nonlinear characteristics of the power system [24], [25], [26].

Transient stability studies are conducted when new generating and transmitting facilities are planned. The studies help determining the nature of the relaying system needed, critical clearing time of circuit breakers, voltage level of, and transfer capability between systems [26].

The behavior of a synchronous machine for stable and unstable situations is illustrated in Figure 10. If the resulting angular separation between the machines remains within certain bounds, the system maintains synchronism and therefore stability. The figure shows the rotor angle response for a stable case and for two unstable cases [24], [25].

In the stable case, Case 1, the rotor angle first increases to maximum, then decreases and oscillates with decreasing amplitude until it reaches a steady state. In Case 2, the rotor angle increases continuously until synchronism is lost. This form of instability is referred to as first-swing instability and is caused by insufficient synchronizing torque. The first swing is of primary importance but in this period the generator is suddenly subjected to an appreciable change in its output power causing its rotor to accelerate (or decelerate) at a rate large enough to threaten loss of synchronism.

In Case 3, the system is stable for the first swing but becomes unstable as a result of growing oscillations as the end state is approached. This form of instability generally occurs when the post-fault steady-state condition itself is small-signal unstable and not necessary as a result of the transient disturbance [24], [25].

Loss of synchronism because of transient instability, if it occurs, will usually be evident within 2 to 3 seconds of the initial disturbance so the study period of transient stability studies is usually limited to 3-5 seconds following the disturbance [24], [25].
For most disturbances, oscillations are of such magnitude that linearization is not permissible and the nonlinear swing equation must be solved.

A method known as the *equal-area criterion* can be used to determine whether the rotor angle increases indefinitely or oscillates about an equilibrium point. The method is only applicable to a one-machine system connected to an infinite bus or a two-machine system, but it helps in understanding basic factors that influence the transient stability of any system [24], [26].

![Figure 11: Simplified model of single-machine infinite bus system [24].](image)

The system in Figure 11 is a simplified model of a single-machine connected to an infinite bus where the generator's electrical power output is:

\[
P_e = \frac{E'E_B}{X_T} \sin \delta = P_{\text{max}} \sin \delta \tag{3.1}
\]

where

\[
P_{\text{max}} = \frac{E'E_B}{X_T} \tag{3.2}
\]

Assuming the mechanical power input \(P_m\) is equal to the steady state electrical power \(P_e\). Let us examine the transient behavior of the system to a sudden increase in the mechanical power input, from an initial value of \(P_{m0}\) to \(P_{m1}\). The power angle variation and the rotor angle response to this step change in mechanical power can be seen in Figure 12.
The rotor angle cannot change instantly from the initial value of $\delta_0$ to $\delta_1$ corresponding to a new equilibrium point from $a$ to $b$ at which $P_e = P_m$, because of the inertia of the rotor. The mechanical power is then in excess of the electrical power and the resulting accelerating torque causes the rotor to accelerate from the initial operating point $a$ toward the new equilibrium point $b$.[24]

The difference between $P_m$ and $P_e$ at any instance represents the accelerating power and when point $b$ is reached, the accelerating power is zero, but the rotor speed is higher than the synchronous speed $\omega_0$ (the frequency of the infinite bus voltage), hence the rotor angle continues to increase. $P_e$ is greater than $P_m$ and the rotor decelerates for values delta higher than $\delta_1$.[24]

The rotor speed recovers, at some peak value of $\delta_m$, to the synchronous value of $\omega_0$ but $P_e$ is higher than $P_m$. So the rotor continues to decelerate with the speed dropping below $\omega_0$; the operating point retraces the $P_e-\delta$ curve from $c$ to $b$ and then to $a$.

The rotor angle oscillates indefinitely about the new equilibrium angle $\delta_1$ with constant amplitude as shown by the time plot of $\delta$ in Figure 12(b) [24].

The equal area criterion can be used to determine the maximum permissible increase in $P_m$ for the system of Figure 11. The stability is maintained only if the area $A_2$ of Figure 12(a) is at least equal to the area $A_1$. If $A_1$ is greater than $A_2$, then $\delta_m > \delta_L$ and stability will be lost. This is because, for $\delta > \delta_L$, $P_m$ is larger than $P_e$ and the net torque is accelerating rather than decelerating [24].

There are two factors which indicate the relative stability of a generating unit, the angular swing of the machine during and following fault conditions and the critical clearing time.

The smaller the $H$ constant is, the smaller the angular swing gets during any time interval. $P_{\text{max}}$ decreases as the transient reactance, $X_{d}'$, of the machine increases because the transient reactance forms part of the overall series reactance which is the reciprocal of the transfer admittance of the system. I.e. any developments which lower the $H$ constant and increase transient reactance $X_{d}'$ of the machine cause the critical clearing time to decrease and lessen the probability of maintaining stability under transient conditions [27].

When power is transmitted during a fault, the equal area criterion is applied. Looking at Figure 13 we see that all three power curves for three periods, before a fault, during a fault and after the fault is cleared. Before the fault, the power that can be transmitted is $P_{\text{max}} \sin \delta$. During the fault the power $r_1 P_{\text{max}} \sin \delta$ can be transmitted and the power that can be transmitted after the fault is cleared is $r_2 P_{\text{max}} \sin \delta$. $\delta_{cr}$ is the critical clearing angle.

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From Figure 13 we can see that all three power curves are lowered when $P_{\text{max}}$ is decreased. Therefore for smaller $P_{\text{max}}$ and for a given shaft power $P_m$ the initial rotor angle $\delta_0$ is increased, $\delta_{\text{max}}$ is decreased, and there is smaller difference between $\delta_0$ and $\delta_{cr}$. The result is that a decreased $P_{\text{max}}$ constrains a machine to swing through a smaller angle from its original position before it reaches the critical clearing angle.
3.1.2 Small-Signal Stability

Small-signal stability is the ability of the power system to maintain synchronism under small disturbances that occur continually on the system because of small variations in loads and generation. These disturbances are assumed to be sufficiently small so the nonlinear differential and algebraic equations of the system can be linearized for the purpose of analysis [24].

The system’s responses to the small-disturbances depend on many factors as the initial operating point, the transmission system strength, and the type of generator excitation controls used [24].

Small-signal instability is a result of:
- steady increase in generator rotor angle due to lack of sufficient synchronizing torque, or
- rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

The lack of sufficient synchronizing torque causes instability for power systems where generators are connected radially in the absence of automatic voltage regulators (i.e., with a constant field voltage). However, the voltage regulators are continuously acting; consequently, the small-signal stability is established by ensuring sufficient damping of the system oscillation where the instability results in increasing oscillations.

Small-signal stability instability in today’s systems is usually because of an insufficient damping of the system oscillations. The linear techniques used in the small-signal studies provide valuable information about the inherent dynamic characteristics of the power system that is helpful for planning and designing of the system [24].

3.2 Voltage Stability

Voltage stability is the ability of a power system to maintain acceptable voltages at all buses under normal operating conditions after a disturbance.

A power system becomes voltage instable when, a disturbance or change in system condition, causes a progressive and uncontrollable voltage drop. The main cause for the instability is a lack of reactive power, i.e., the system is voltage instable if, for at least one bus in the system, the bus voltage decreases as the reactive power injection at the same bus is increased.

“Voltage instability is essentially a local phenomenon; however, its consequences may have a widespread impact. Voltage collapse is more complex than simple voltage instability and is usually the result of a sequence of events accompanying voltage instability leading to a low-voltage profile in a significant part of the power system” [24].

“Voltage stability problems normally occur in heavily stressed systems. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the underlying problems is an inherent weakness in the power system. In addition to the strength of transmission network and power transfer levels, the principal factors contributing to voltage collapse are the generator reactive power/voltage control limits, load characteristics, characteristics of reactive compensation devices, and the action of voltage control devices such as transformer under-load tap changers” [24].

The ability of a power system to maintain voltage stability under normal and abnormal steady state operating conditions is determined by the objectives of a PV and QV curves. The curves show the voltage collapse point of the buses in the power system, the maximum transfer of power between buses before the voltage collapse point and the size of reactive power compensation devices required at relevant buses to prevent voltage collapse.

3.2.1 PV Curves

PV curves are obtained by a parametric study involving a series of AC load flows that monitor the changes in one set of load flow variables with respect to another in a systematic fashion. As power transfer is increased, voltage decreases at some buses on or near the transfer path. The transfer capacity where voltage reaches the low voltage criterion is the low voltage transfer limit. Transfer can continue to increase until the solution identifies a condition of voltage collapse; this is the voltage collapse transfer limit [24].
By looking at the diagram of Figure 14 where:

\[ I = \frac{E_s}{\sqrt{F} Z_{LN}} \]  
\[ V_R = \frac{1}{\sqrt{F} Z_{LN}} E_s \]  
\[ P_R = \frac{Z_{LD}^2}{F \left( \frac{E_s}{Z_{LN}} \right)^2} \cos \phi \]  
\[ F = 1 + \left( \frac{Z_{LD}}{Z_{LN}} \right)^2 + 2 \left( \frac{Z_{LD}}{Z_{LN}} \right) \cos (\theta - \phi) \]

it can be seen that the loading of the network can be increased by decreasing the value of \( Z_{LD} \). This is done with \( E_s \), load power factor and line parameters fixed. From equation (3.5), as \( Z_{LD} \) is decreased gradually the load power, \( P_R \), increases, hence the power transmitted will increase. As the value of \( Z_{LD} \) approaches \( Z_{LN} \) the value of \( P_R \) starts to decrease gradually due to \( F \). However, from equation (3.4) as \( Z_{LD} \) decreases the receiving voltage \( V_R \) decreases gradually [24].

The power system becomes voltage instable at the knee point of the PV curve, see Figure 15, where the voltage drops more rapidly with an increase in the transfer power flow. A satisfactory operating condition can be ensured by preventing an operation at or near the stability limit [29].

### 3.2.2 QV Curves

QV curves, similar to PV curves, are obtained through a series of AC load flow calculations. QV curves are used to determine the reactive power demand by a bus or buses as voltage level changes. Starting with the existing reactive loading at a bus, the voltage at the bus can be computed for a series of power flows as the reactive load is increased in steps, until the power flow experiences convergence difficulties as the system approaches the voltage collapse point [28]. QV curves for different range of system loading can be seen in Figure 16.

Revisiting equations (3.4) and (3.5), we see that the power factor of the load has a significant impact on the overall equations. This is to be expected since the voltage drop in the line is a function of both active and reactive power transfer. Hence, the QV curves may also be used to assess voltage stability of the system. The system is
stable when \( Q \) is increased in all buses and \( V \) increases and instable when \( Q \) is increased and \( V \) in at least one bus decreases [28].

The bottom of the QV curve, where the change of reactive power, \( Q \), with respect to voltage, \( V \) (or derivative \( dQ/dV \)) is equal to zero, represents the voltage stability limit. Since all reactive power compensator devices are designed to operate satisfactorily when an increase in \( Q \) is accompanied by an increase in \( V \), the operation on the right side of the QV curve is stable, whereas the operation on the left side is unstable [28].

The bottom of the QV curves, also, defines the minimum reactive power requirement for the stable operation. Hence, the QV curve can be used to examine the type and size of compensation needed to provide voltage stability [28].

### 3.3 Mid-Term & Long-Term Stability

The terms long-term and mid-term stability were introduced as a result of the need to deal with problems associated with dynamic response of power system to severe upsets that result in large excursion of voltage, frequency, and power flow. These upsets invoke the actions of slow processes, controls, and protection that are not modeled in conventional transient stability studies. The characteristic times of the processes and devices activated by the large voltage and frequency shifts will range from a matter of seconds, for devices such as generators control and protections, to several minutes for devices such as prime mover energy supply systems and load-voltage regulators.

“Generally, the long-term and mid-term stability problems are associated with inadequacies in equipment responses, poor coordination of control and protection equipment, or insufficient active/reactive power reserves [24].”

The distinction between mid-term and long-term stability is primarily based on the phenomena being analyzed and the system representation used rather than the time period involved, particularly with regard to fast transients and inter-machine oscillations. But as improved analytical techniques for simulation of slow as well as fast dynamics become available and more experience is gained, the distinction between mid-term and long-term stability becomes less significant [24].

#### 3.3.1 Long-Term Stability

Long-term stability analysis with time period range of a few minutes to 10’s of minutes, assumes that inter-machine synchronizing power oscillations have damped out with the result being uniform system frequency.

In long-term stability studies the focus is on the slower and longer-duration phenomena that accompany large-scale system upsets and on the resulting large, sustained mismatches between generation and consumption of active and reactive power. “These phenomena include: boiler dynamics of thermal units, penstock and conduit dynamics of hydro units, automatic generation control, power plant and transmission system protection/controls, transformer saturation, and off-nominal frequency effects on loads and the network” [24].
These studies are usually concerned with system response to major disturbances that involve contingencies beyond the normal system design criteria. This may include cascading and splitting of the power system into a number of separate islands with the generators in each island remaining in synchronism. In this case the stability is a question of whether or not each island will reach an acceptable state of operating equilibrium with minimal loss of load and it is determined by the overall response of the island as evidenced by its mean frequency, rather than the relative motion of machines [24].

3.3.2 Mid-Term Stability
The mid-term stability response represents the transition between short-term and long-term response with the typical time period range from 10 seconds to a few minutes. Mid-term stability studies focus on synchronizing power oscillations between machines, including the effects of some of the slower phenomena, and possibly large voltage or frequency excursions [24].

3.4 Switching Transients
3.4.1 Voltage Transients on Closing and Reclosing Lines
As a switch closes a certain voltage exists across the switch contacts. If the line is de-energized this could be anywhere between zero and the peak system voltage. At the moment the contacts make or are joined by a prestriking discharge, this voltage disappears only to reappear distributed around the circuit. The distribution will be in accordance with the impedance of the parts of the circuit [29].

Looking back into the system from the circuit breaker, we see the source impedances paralleled by the surge impedance of however many lines are connected at the time. This combined impedance we can call $Z_1$. Looking toward the line we see its surge impedance, which momentarily will appear resistive, i.e. $Z_0 = R$. If the instantaneous voltage is $V$, a fraction

$$V_L = \frac{R}{Z_1 + R}V$$

(3.7)

will momentarily appear across the line, and across the source fraction

$$V_S = \frac{Z_1}{R + Z_1}V$$

(3.8)

will appear. Since $Z_1$ is in general complex equations 1 and 2 are most readily evaluated by operational methods:

$$V_L(s) = \frac{z_1(s)}{R + z_1(s)}V$$

(3.9)

Evidently, if $R >> Z_1$, most of the voltage will appear across the line. This is the condition that will prevail on a stiff system [29].

This voltage will travel down the line as a wave and be reflected from its remote end, returning to the source in due course. If the far end of the line is open-circuited the reflected wave will add to the incident wave, so that a voltage approaching 2 per unit will be impressed on the line [29].

A common practice on utility system is to reclose a breaker as rapidly as possible after it has interrupted a fault. This allows the service to be restored quickly if the fault is of a transient nature, as many of them are. In the event that the transient fault is a single line-to-ground fault it is possible to leave a considerable voltage trapped on the un-faulted lines at the time of disconnecting, if the are open-circuited. When the switch recloses it may do so on the opposite polarity to the trapped charge; leading to the theoretical doubling of the traveling wave voltage [29].
4 Transient Stability Study

In this chapter we examine a 290 MW load where the power demand is met on the first hand with new geothermal plants in the region near the existing geothermal plant Krafla in North-Eastern Iceland and on the other hand with hydro plants. The aim is to compare the critical clearing time when the nearby generation is geothermal versus hydraulic.

The critical clearing time is determined with transient stability study where we examine if the system remains stable when the system experiences faults on transmission lines located near the new load and the new generation plants. As we saw in Figure 10, if the angular separation between machines remains within certain bounds after a fault, the system maintains synchronism and therefore stability.

For the study we use the program PSS/E Dynamics from PTI Siemens and the data for the Icelandic transmission system was provided by Landsnet, the Icelandic Transmission Company.

We look at the critical clearing time for fault on lines, KR2, KR1, and RA1. The location of these lines, shown in red, and the layout of the system in Northeastern Iceland can be seen in Figure 17.

4.1 Fault on KR2

One of the main concerns is the outage on the line KR2 and the influence of this outage on the system stability. This fault is known to cause problems in the system today because when this line is not in service all the power transfer needed in Eastern Iceland goes through a transformer in Sigalda power plant that gets overloaded if there is not enough local production. Layout of the Icelandic transmission system can be found in Appendix 1.

4.1.1 Analysis with Geothermal Plants

For all the faults and both types of generation, we find the critical clearing time for the system where the faulted transmission lines are disconnected/opened after the fault is cleared and when they are not disconnected.

For the sequence of operation, we first run the system in steady state for 2 seconds before applying the fault. Then faults with different duration are applied and the critical clearing time is determined using the first swing criterion for rotor angle difference, i.e. if the angle difference does not grow monotonically the system is stable.

4.1.1.1 Opened Branch

In the simulations below we look at the angle difference for the Rangárvellir bus and the Fjötsdalur bus. Taking the angle at the Rangárvellir bus as a reference, the angle at the Fjötsdalur bus is plotted as a relative to that
angle, i.e. the angle difference seen in Figure 18 is the angle difference between Rangárvellir bus and Fljótsdalur bus with the angle at Rangárvellir bus as a reference.

For the clearing time of 120 ms, which is a common clearing time for circuit breakers, it can be seen in Figure 18 that the system is stable for the first swing.

![Figure 18: Angle difference vs. time for fault on KR2 that is cleared after 120 ms.](image)

![Figure 19: Voltage vs. time for fault on KR2 that is cleared after 120 ms.](image)

In Figure 19 we see that the voltage on the Rangárvellir bus goes down to 0.3 p.u. during the fault but then recovers very quickly after the fault is cleared.
In Figure 20 we see that when the clearing time is increased to 260 ms the first simulation is still stable, according to the first swing criterion, but the amplitude of the oscillation is larger.

**Figure 20:** Angle difference vs. time for fault on KR2 that is cleared after 260 ms.

**Figure 21:** Voltage vs. time for fault on KR2 that is cleared after 260 ms.
We see in Figure 22 that increasing the short circuit time to 270 ms the first oscillation becomes unstable and we therefore draw the conclusion that the critical clearing time, when the load demand is met with geothermal plants and a fault occurs on KR2 and the line is disconnected, is 260 ms.

Figure 22: Angle difference vs. time for fault on KR2 that is cleared after 270 ms.

Figure 23: Voltage vs. time for fault on KR2 that is cleared after 270 ms.
4.1.1.2 Not Opened Branch

By keeping the branch, i.e. not disconnecting the line after the fault has been cleared, the system remains stable for longer clearing time.

For clearing time of 310 ms the system still maintains synchronism as can be seen in Figure 24.

![Figure 24: Angle difference vs. time for fault on KR2 that is cleared after 310 ms and the line is not tripped.](image1)

Increasing the clearing time to 320 ms the first oscillation becomes unstable, see Figure 25, and we therefore draw the conclusion that the critical clearing time, when the load demand is met with geothermal plants and a fault occurs on KR2 and the line is not disconnected, is 310 ms.

![Figure 25: Angle difference vs. time for fault on KR2 that is cleared after 320 ms and the line is not tripped.](image2)
4.1.2 Analysis with Hydro Plants

Now we look at the same fault, for cases where the power demand for the new smelter is met with hydro plants.

4.1.2.1 Opened Branch

We see in Figure 26 that for clearing time of 220 ms the simulation and the system are stable.

Increasing the clearing time the to 230 ms the first oscillation becomes unstable, see Figure 27, and we therefore draw the conclusion that the critical clearing time, when the load demand is met with hydro plants and a fault occurs on KR2 and the line is disconnected, is 230 ms.

Figure 26: Angle difference vs. time for fault on KR2 that is cleared after 220 ms.

Figure 27: Angle difference vs. time for fault on KR2 that is cleared after 230 ms.
4.1.2.2 Not Opened Branch
As before, keeping the branch, i.e. not disconnecting the line after the fault has been cleared, the system remains stable for longer clearing time.

For clearing time of 240 ms the system still maintains synchronism as seen in Figure 28.

In Figure 29 we see that increasing the clearing time to 250 ms the first oscillation becomes instable and we therefore draw the conclusion that the critical clearing time, when the load demand is met with hydro plants and the fault occurs on KR2 and the line is not disconnected, is 240 ms.
4.1.3 Results

The critical clearing times for a fault on KR2 are compared in Table 1 when the load is supplied by hydro versus geothermal plants. The system in this case will be more stable when geothermal plants are used to meet the power demand of the new load. This is so because the inertia of geothermal power plants is higher than for hydro plants.

In Section 3.1.1, we saw that a smaller inertia decreases the critical clearing time. The reason is that the smaller the $H$ constant the smaller $P_{\text{max}}$. A smaller $P_{\text{max}}$ constrains a machine to swing through a smaller angle from its original position before it reaches the critical clearing angle. Therefore, smaller $H$ constant decreases the critical clearing time and lowers the probability of the system to maintain stability.

<table>
<thead>
<tr>
<th>FAULT ON KR2</th>
<th>Geothermal Plants</th>
<th>Hydro Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>With branch tripping</td>
<td>260 ms</td>
<td>220 ms</td>
</tr>
<tr>
<td>With no tripping</td>
<td>310 ms</td>
<td>240 ms</td>
</tr>
</tbody>
</table>

Table 1: Critical clearing time after a fault on KR2.
4.2 Fault on KR1

For this fault we look at the same buses as for a fault on KR2, i.e. the Rangárvellir bus and Fljótsdalur bus, where the angle at the Fljótsdalur bus is plotted as a relative to the angle at the Rangárvellir bus.

The system does not become transient instable for this fault no matter how long the clearing time is. The system's angular difference is shown below for clearing time of 3 minutes for cases where the power demand is met with geothermal plants, see Figure 30; and for hydro plants see Figure 31. The angle difference does not grow monotonically so the system is stable according to the first swing criterion. The system will become voltage instable after such long fault time, but due to some limitations in the program we could not look further into this issue.

The simulations made are limited to short time, under 10 seconds. Because the model of the Icelandic transmission system does not include all the control and protection equipment needed for mid-term and long-term stability studies. The simulations show that the system becomes unstable with a slowly increasing oscillation. This is true even when there is no disturbance. The systems itself is stable and operating satisfactory, but the program, using the most accurate data available, predicts that the systems is instable to small signals.

4.2.1 Analysis with Geothermal Plants

![Figure 30: Angle difference vs. time for fault on KR1 that is cleared after 3 minutes.](image-url)
4.2.2 Analysis with Hydro Plants

Figure 31: Angle difference vs. time for fault on KR1 that is cleared after 3 minutes.
4.3 Fault on RA1

For this fault we look at the buses at Rangárvellir and Blanda. Blanda is a hydro plant and also the swing bus for the system.

4.3.1 Analysis with Geothermal Plants

4.3.1.1 Opened Branch

For the critical clearing time of 280 ms, see Figure 32, the system is stable according to the first swing criterion but when it is increased to 290, see Figure 33, it becomes unstable.

Taking the angle at the Blanda bus as a reference, the angle at the Rangárvellir bus is plotted as a relative to that angle, i.e. the angle difference seen in Figure 32 and Figure 33 is the angle difference between Blanda bus and Rangárvellir bus with the angle at Blanda bus as a reference.

![Figure 32: Angle difference vs. time for fault on RA1 that is cleared after 280 ms.](image1)

![Figure 33: Angle difference vs. time for fault on RA1 that is cleared after 290 ms.](image2)
4.3.1.2 Not Opened Branch

In Figure 34 and Figure 35 we see that for the critical clearing time of 420 ms the system is stable according to the first swing criterion but when it is increased to 430 it becomes instable. Therefore we draw the conclusion that the critical clearing time, when the load demand is met with geothermal plants, fault occurs on RA1 and the line is not opened when the fault is cleared, is 420 ms.

Figure 34: Angle difference vs. time for fault on RA1 that is cleared after 420 ms.

Figure 35: Angle difference vs. time for fault on RA1 that is cleared after 430 ms.
4.3.2 Analysis with Hydro Plants

4.3.2.1 Opened Branch

When the load demand is met with hydro plants and fault occurs on RA1, and the line is opened when the fault is cleared, is 280 ms as can be seen from Figure 36 and Figure 37.

Figure 36: Angle difference vs. time for fault on RA1 that is cleared after 280 ms.

Figure 37: Angle difference vs. time for fault on RA1 that is cleared after 290 ms.
4.3.2.2 Not Opened Branch

From Figure 38 and Figure 39 we draw the conclusion that the critical clearing time is 420 ms when the load demand is met with hydro plants, a fault occurs on RA1, and the line is not opened when the fault is cleared.

In Figure 38 we see that the system remains stable for the clearing time of 420 ms. When the clearing time is increased to 430 ms, see Figure 39, the angle difference grows monotonically; therefore, the system loses synchronism and becomes instable.

![Figure 38: Angle difference vs. time for fault on RA1 that is cleared after 420 ms.](image)

![Figure 39: Angle difference vs. time for fault on RA1 that is cleared after 430 ms.](image)
4.3.3 Results

We can see in Table 2 that for this fault the type of generation does not matter, the critical clearing time is the same. The system is as stable for both geothermal and hydro plants.

For a fault on RA1, the transmission line is probably located far enough from the load and generation site for the inertia to play a part in the critical clearing time. In this case, the critical clearing time is the same for systems where the power demand is met with geothermal plants or hydro plants.

<table>
<thead>
<tr>
<th>FAULT ON RA1</th>
<th>Geothermal Plants</th>
<th>Hydro Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>With branch tripping</td>
<td>280 ms</td>
<td>280 ms</td>
</tr>
<tr>
<td>With no tripping</td>
<td>420 ms</td>
<td>420 ms</td>
</tr>
</tbody>
</table>

Table 2: Critical clearing time after a fault on RA1.
5 Voltage Stability Study

In this chapter we examine the connection of a large load to the transmission system at the same location as in chapter 4 in Northern Iceland, see Figure 40. For this case the power demand is met with two geothermal plants and with one hydro plant.

The new geothermal plants are assumed to be located at Krafla (a new plant next to the one there already) and at Peistareykir. The hydro power plant is assumed to be located nearby. These locations have been studied and are considered attractive power generation options.

![Figure 40: Layout of the system with the new load and power plants.]

In Iceland, most power intensive industries are aluminum smelters. Common startup size of the smelters is 150 thousand tons per year which is around 250 MW.

The local load in this area before applying the new load is only 77 MW so this load is a very large addition to this weak point in the transmission system and clearly some reinforcement have to be added. The connection to the transmission system can be either 132 kV or 220 kV. Because it is likely that the load will increase in the future and also because the 132 kV ring is already weak and has to be rebuilt in the years to come, we will focus on a 220 kV extension of the system.

With the N-1 criterion in mind, using voltage stability studies, we find which reinforcements are needed to connect the load and the new plants to the transmission system. As before we use data from the Icelandic transmission company, Landsnet, and for the simulation we use the PSS/E Load flow program from PTI Siemens. The power factor of the new load/smelter is set 0.97.

5.1 System Reinforcements

The needed reinforcements to connect the load to the transmission system with N-1 criteria in mind are:

- New 220/132 kV transformer at Krafla.
- New transmission 220 kV transmission line between Krafla and the new hydro plant.
- Two 220 kV transmission lines between Krafla and Peistareykir.
- Two 220 kV transmission lines between Peistareykir and Húsavík.

5.2 Contingency Analysis

Contingency analysis for outages of all 132 kV ring and the new 220 kV lines were made where all faults are considered 3 phase faults.

When the line Hrafnabjörg-Krafla 90 MW gets disconnected from the transmission system the swing bus does not have enough spare generation to cover the loss. Other power plants have enough generation reserve; however some relays need to be tuned or installed in order to prevent a blackout. The critical point is determined by PV analysis in Section 5.3.
If the load itself gets disconnected the system becomes unstable because the swing bus cannot reduce its production by 250 MW. Precise adjustment of relays will be needed to disconnect the 220 kV bus at Krafla for the rest of the system to remain stable.

By decreasing the load and the corresponding local generation it can be seen that if the load is 163 MW or less the system will remain stable when the load is disconnected. Reactive power is needed to keep the voltage at the load bus near 1.0 p.u. in base cases. The minimum reactive power demand is determined by QV analysis in Section 5.4.

### 5.3 PV Analysis

We saw in section 3.2.1 that the voltage collapse transfer limit is determined by increasing the power transfer until the solution identifies a condition of voltage collapse. The system becomes voltage unstable where the voltage drops more rapidly with an increase in the transfer power flow.

The maximum transfer limit is determined by increasing the load on the Húsavík bus along with the generation at the new generation plants. In Figure 41 we see the PV curves for the base case and five outages that limit the most the increasing of the load.

The PV curves on Figure 41 show that the loss of the line Krafla-Hydro plant limits most the increasing of the load. The PV curve outage is shown isolated at Figure 42.

The curve marked as Base Case is when there is no outage in the system.
Figure 42: PV curve at the Húsavík-bus for the Krafla-Hydro plant outage

Point A represents the system with the new 250 MW load. Point B represents a case operating near the critical point (with 40 MW load increase). Point C, the critical point, is where the voltage collapse occurs (49 MW load increase). A satisfactory operating condition can be ensured by preventing an operation at or near the stability limit.
5.4 QV Analysis

In section 3.2.2 we saw that QV curves are used to determine the reactive power demand by a bus or buses as voltage level changes.

Starting with the existing reactive loading at a bus, the voltage at the bus is computed until the power flow experiences convergence difficulties as the system approaches the voltage collapse point. The system is stable when $Q$ is increased in all buses and $V$ increases and unstable when $Q$ is increased and $V$ in at least one bus decreases.

QV curves for the three operating points of Figure 42 are computed and shown in Figure 43 - Figure 45. The curves show the reactive power demand for the base case and seven outages.

For point A we find the reactive power demand for the base case. Point B is of no significance but shows a point where the system operation is still possible. The QV curves for point C show us a very heavily loaded system as the system approaches the voltage collapse point.

![Figure 43: QV curve for the 250 MW load (Base Case) at the Húsavik bus.](image-url)
Figure 44: QV Curve for the 290 MW Load (Operation near the Critical Point) at the Húsavík Bus.
5.5 Results

The PV curve on Figure 41 shows that the loss of the line Krafla-Hydro plant limits the increase of the load. On the same graph, the critical point (voltage collapse point) was found at 49 MW. I.e. if the load is increased more than 49 MW at the Húsavík bus with no added shunt capacitors the system will become unstable because of the voltage collapse at the Húsavík bus.

The Krafla-Hydro plant contingency graph (purple) on the QV curves in Figure 43 - Figure 45 follow the schematics of Figure 16 very well. The bus is lightly loaded on Figure 43, heavily loaded on Figure 44, and very heavily loaded on Figure 45. The part of stability and instability are also clear.

From the QV curves and the listed $Q_{\text{Min}}$ the reactive power demand for the bus is the highest during normal operation (Base Case). But when outages of the lines Hryggstekkur-Fljótsdalur and Krafla-Hydro plant occur the reactive power on the Húsavík bus becomes too high and the capacitor absorbs reactive power.

Figure 45: QV Curve for the 299 MW Load (The Critical Point) at the Húsavík bus.
6 Switching Transients

Most faults on transmission lines are single line-to-ground faults. Opening and reclosing only the faulted phase, single-pole switching, rather than all three phases, reduces system stresses and results in an improvement in transient stability [24].

Single pole switching uses separate opening mechanisms on each phase so for single line-to-ground faults the relaying is designed to trip only the faulted phase followed by fast reclosing within 0.5-1.5 seconds. During the period when the one phase is open half of the full power is transferred over the remaining two phases [24].

Quite severe overvoltages can result from energizing a line, and yet higher voltages as a consequence of re-energizing after a momentary interruption. Therefore the switching surges become a limiting factor in the choice of insulation levels and arrester characteristics for high voltage circuits [29].

6.1 Single Pole Switching and Reclosing

In this section we look at a circuit that represents a part of the Icelandic power transmission system.

![Figure 46: The Icelandic transmission system.](image-url)

For that we use the Alternating Transient Program, ATP. The circuit can be seen in Figure 48. Line 1 represents KR1. Line 2 represents the lines: VA1, HR1, LV1, BL1, BL2, RA1 and KR1. Line 3 represents: SU3, HR1 and SI2. Line 4 represents: FL2, TE1, HO1, PB1 and SI4. A larger figure of the Icelandic transmission system can be found in Appendix 1.
Our goal is to simulate the single pole switching and reclosing. We apply a single-line-to-ground fault to phase C in transmission line 1. The switches, that represent the circuit breakers, perform a single pole switching and reclosing operation before all three phases are opened.

In essence the process is:

- Run the circuit for steady state.
- Apply a single-line-to-ground short circuit in the middle of the line.
- Single-pole switching and reclosing.
- Open all three phases.

What we expect to get as a result is:

- During the SLG fault large current in the faulted phase accompanied with small voltage.
- When opening the switch the current in that phase should reduce to almost zero.
- When reclosing the conditions will depend on the state of the short circuit.
- After opening the three phases some voltage will be trapped in the un-faulted phases.

### 6.1.1 Line Parameters

The lines are modeled using the distributed transposed line models in ATP.

For line 1 we use three single phase lines and the parameters required for that model are:

- $R/l$ = Resistance pr. length in [Ohm/length].
- $A$ = inductance L' in [mH/length].
- $B$ = capacitance C' in [µF/length].
- $l$ = length of line.

For lines 2-4 we use three phase lines and the parameters required for that model are:

- $R/l+$ = Pos. sequence resistance pr. length in [Ohm/length].
- $R/0$ = Zero sequence resistance pr. length in [Ohm/length].
- $A+$ = Pos. sequence inductance L in [mH/length].
- $A0$ = Zero sequence inductance [mH/length].
- $B+$ = Pos. sequence capacitance C in [µF/length].
B0 = Zero sequence capacitance in [µF/length].

l = length of line.

The data given for the transmission lines are the p.u. values of R, X, and B. To get the values in the desired form we use the following equations [24],[28]:

\[
R = \frac{R_{pu} \cdot (V_{LL})^2 / S_{BASE}}{l} \quad [\Omega/\text{mile}] \\
X_L = \frac{X_{pu} \cdot (V_{LL})^2 / S_{BASE}}{l} \quad [\Omega/\text{mile}] \\
B_C = \frac{B_{Cpu}}{l \cdot (V_{LL})^2 / S_{BASE}} \quad [S/\text{mile}] \\
L = \frac{X_L}{\omega} \quad [\text{mH/mile}] \\
C = \frac{B_C}{\omega} \quad [\mu\text{F/mile}] 
\]

6.1.1.1 Parameters for Line #1

The given parameters are following:

<table>
<thead>
<tr>
<th>Line #1</th>
<th>Length [km]</th>
<th>R [pu]</th>
<th>X [pu]</th>
<th>Bc [pu]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KR2</td>
<td>142.4</td>
<td>0.06485</td>
<td>0.29293</td>
<td>0.06414</td>
</tr>
</tbody>
</table>

Using equations (6.1) – (6.5) and that VLL is 132 kV and that in Iceland the frequency is 50 Hz we get:

<table>
<thead>
<tr>
<th>Line #1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>C</td>
</tr>
</tbody>
</table>

6.1.1.2 Parameters for Lines #2, #3 & #4

The given parameters are following:

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VA1</td>
<td>20.0</td>
<td>0.01023</td>
<td>0.04667</td>
<td>0.00996</td>
<td>0.02683</td>
<td>0.15518</td>
<td>0.00623</td>
</tr>
<tr>
<td>HR1</td>
<td>76.9</td>
<td>0.03731</td>
<td>0.17832</td>
<td>0.03853</td>
<td>0.10116</td>
<td>0.59722</td>
<td>0.02939</td>
</tr>
<tr>
<td>LV1</td>
<td>72.6</td>
<td>0.03822</td>
<td>0.16941</td>
<td>0.03624</td>
<td>0.09858</td>
<td>0.56543</td>
<td>0.02255</td>
</tr>
<tr>
<td>BL1</td>
<td>32.4</td>
<td>0.01575</td>
<td>0.07424</td>
<td>0.01639</td>
<td>0.04262</td>
<td>0.25258</td>
<td>0.01000</td>
</tr>
<tr>
<td>BL2</td>
<td>32.2</td>
<td>0.01458</td>
<td>0.07515</td>
<td>0.01600</td>
<td>0.04132</td>
<td>0.24740</td>
<td>0.01022</td>
</tr>
<tr>
<td>RA1</td>
<td>87.4</td>
<td>0.08588</td>
<td>0.21405</td>
<td>0.04141</td>
<td>0.15845</td>
<td>0.69015</td>
<td>0.02626</td>
</tr>
<tr>
<td>KR1</td>
<td>82.1</td>
<td>0.04316</td>
<td>0.19191</td>
<td>0.04080</td>
<td>0.11133</td>
<td>0.63735</td>
<td>0.02556</td>
</tr>
<tr>
<td>Total</td>
<td>403.6</td>
<td>0.24510</td>
<td>0.94975</td>
<td>0.19933</td>
<td>0.58029</td>
<td>3.14531</td>
<td>0.12475</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SU3</td>
<td>120.0</td>
<td>0.00574</td>
<td>0.08190</td>
<td>0.20218</td>
<td>0.03948</td>
<td>0.37539</td>
<td>0.14223</td>
</tr>
<tr>
<td>HR1</td>
<td>19.5</td>
<td>0.00180</td>
<td>0.01737</td>
<td>0.02560</td>
<td>0.00760</td>
<td>0.05022</td>
<td>0.01872</td>
</tr>
<tr>
<td>SI2</td>
<td>8.7</td>
<td>0.00079</td>
<td>0.00766</td>
<td>0.01129</td>
<td>0.00335</td>
<td>0.02215</td>
<td>0.00825</td>
</tr>
<tr>
<td>Total</td>
<td>148.2</td>
<td>0.00833</td>
<td>0.10693</td>
<td>0.23907</td>
<td>0.05043</td>
<td>0.44776</td>
<td>0.16920</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FL2</td>
<td>7.5</td>
<td>0.01322</td>
<td>0.04968</td>
<td>0.08516</td>
<td>0.03506</td>
<td>0.23132</td>
<td>0.00856</td>
</tr>
</tbody>
</table>
### 6.2 Simulations and Observations

#### Voltage sources
- Line #1: $\text{TE1}$, $\text{HO1}$, $\text{PB1}$, $\text{SI4}$
- Line #3: $\text{TE1}$, $\text{HO1}$, $\text{PB1}$, $\text{SI4}$
- Total: $\text{TE1}$, $\text{HO1}$, $\text{PB1}$, $\text{SI4}$

Using equations (6.1) – (6.8) and as before that $V_{LL}$ is 132 kV and $f = 50$ Hz we get:

<table>
<thead>
<tr>
<th>Line</th>
<th>$R$ [Ω/mile]</th>
<th>$L$ [mH/mile]</th>
<th>$C$ [µF/mile]</th>
<th>$R_{\text{ZERO}}$ [Ω/mile]</th>
<th>$L_{\text{ZERO}}$ [mH/mile]</th>
<th>$C_{\text{ZERO}}$ [µF/mile]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line #2</td>
<td>0.16972</td>
<td>2.09336</td>
<td>0.01447</td>
<td>0.40317</td>
<td>6.95598</td>
<td>0.00909</td>
</tr>
<tr>
<td>Line #3</td>
<td>0.04378</td>
<td>1.78893</td>
<td>0.01707</td>
<td>0.26505</td>
<td>7.49102</td>
<td>0.01203</td>
</tr>
<tr>
<td>Line #4</td>
<td>0.13944</td>
<td>2.15034</td>
<td>0.02113</td>
<td>0.38533</td>
<td>7.35810</td>
<td>0.00971</td>
</tr>
</tbody>
</table>

Figure 48: The ATP circuit.

- Phase 1: $Tcl = 0.1$ s, $Top = 0.46$ s
- Phase 2: $Tcl = 0.1$ s, $Top = 0.46$ s
- Phase 3: $Tcl = 0.1$ s, $Top = 0.34$ s
- $Tcl = 0.35$ s, $Top = 0.46$ s
- Voltage sources: 132 kV, $f = 50$ Hz
- SLG fault: $Tcl = 0.30$ s
The voltage across the faulted phase is zero until we connect the line. Then we get small transients and then the voltage settles to the line voltage. At $t = 0.3$ s we apply the fault and during the fault we have a small voltage that then goes to zero when the phase is opened. Single phase reclosing gives us again a small voltage that goes to zero when all three phases are opened.

![Figure 49: The voltage in the faulted phase.](image1)

During the fault, the faulted phase has a very high overcurrent, almost tenfold the size of the current pre-fault. The current then goes to zero when the switch is opened but when the switch is reclosed we get the same overcurrent until the switch is opened again.

![Figure 50: The current in the faulted phase.](image2)

In the other two phases, phase A and B, we get an overvoltage after the reclosing and after all three phases are opened the two phases are still charged due to the voltage that gets trapped in the circuit. As mentioned before,
the amount of charge that is left on the phase depends on the opening time. We also note that for the period of time when one phase is open, the voltage of the unfaulted phases is $\sqrt{3}$ larger.

We get an overvoltage across the switch in the faulted phase during the fault. The voltage goes to 200 kV, which is 1.5 per unit.
6.3 Results

In the un-faulted phases of Line #1, voltage gets trapped. That charge can have a serious effect on the system when the line is reconnected after the fault is cleared. When a voltage gets trapped as in this transmission line, workers need to make sure to discharge the line before fixing the fault.

We get an overvoltage of 1.5 p.u. over the switch in the faulted phase. That overvoltage together with the voltage that gets trapped in the un-faulted phases determines the size of the circuit breakers and the insulation level. If the circuit breakers cannot withstand this overvoltage we might have a restrike when we try to reconnect the transmission line after the fault is cleared.

The overcurrent in the faulted phase is tenfold the size of the current in normal operation and gives us information of how large the conductor we need and how strong its parts have to be to withstand the stresses.
7 Conclusions

7.1 Transient Stability Study

In chapter 4 we examined the critical clearing time for faults on three transmission lines. We saw that a fault on KR2 has the most effect on the system’s transient stability. The critical clearing time for a fault on KR2 can be seen in Table 3. The system in this case will be more stable when geothermal plants are used to meet the power demand of the new load. This is because in this study case the inertia of geothermal power plants is higher than for hydro plants. This agrees with the theory seen in Section 3.1.1, i.e. a machine with smaller inertia yields a reduced critical clearing time. The reason is that the smaller the $H$ constant the smaller $P_{\text{max}}$.

<table>
<thead>
<tr>
<th>FAULT ON KR2</th>
<th>Geothermal Plants</th>
<th>Hydro Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>With branch tripping</td>
<td>260 ms</td>
<td>220 ms</td>
</tr>
<tr>
<td>With no tripping</td>
<td>310 ms</td>
<td>240 ms</td>
</tr>
</tbody>
</table>

Table 3: Critical clearing time after a fault on KR2.

The other two faults, i.e. faults on KR1 and RA1, represent what happens when other transmission lines in the system are disconnected. In the case of a KR1, the faults cause no problems, i.e. the system does not become unstable for the fault no matter how long the clearing time. For a fault on RA1, the transmission line is probably located far enough from the load and generation site for the inertia to play part in the critical clearing time. In this case, the critical clearing time is the same for systems where the power demand is met with geothermal plants or hydro plants.

<table>
<thead>
<tr>
<th>FAULT ON RA1</th>
<th>Geothermal Plants</th>
<th>Hydro Plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>With branch tripping</td>
<td>280 ms</td>
<td>280 ms</td>
</tr>
<tr>
<td>With no tripping</td>
<td>420 ms</td>
<td>420 ms</td>
</tr>
</tbody>
</table>

Table 4: Critical clearing time after a fault on RA1.

7.2 Voltage Stability Study

In chapter 4 we examined the connection of a 250MW load to the transmission system at the same location as in chapter 3, where the power demand was met with two geothermal plants and with one hydro plant.

The maximum size of the load is limited by an outage of the line Krafla-Hydro plant. The voltage collapse point was found from PV curves at 49 MW load increase. Therefore the maximum size of the load is less than 300 MW at the Húsavik bus with no additional shunt capacitors.

The reactive power demand for the load bus is the most, 75 MVAr during a normal operation, i.e. for the base case, in a lightly loaded system. However when the system is very heavily loaded the reactive power on the load bus becomes too high when outages of the lines Hryggstekkur-Fljótsdalur and Krafla-Hydro plant, and the capacitor absorbs reactive power.
7.3 Single Pole Switching and Reclosing

For the line marked as #1 in Figure 48, representing the line KR2, voltage gets trapped in the unfaulted phases. When the line is reconnected after the fault is cleared, this charge can have a serious effect on the system such as restrike.

This trapped voltage together with the overvoltage across the switch in the faulted phase, determines the insulation level of the breaker. The overcurrent in the faulted phase gives us information of how large the conductor we need and how strong its parts have to be to withstand the stresses.

7.4 Answers to the Objective Questions

The objective of this thesis was to get answer to three questions set forth in section 1.2.

- What will happen when a group of geothermal plants are connected to the transmission grid at a weak point of the system?
- What is the difference in the power system stability when a large power demand is met with hydro power plants vs. geothermal plants?
- When planning a new aluminum smelter in northern Iceland, looking at the voltage stability, with the N-1 criteria in mind, which reinforcements are needed to connect the load and the new plants to the transmission system?

Summarized, the conclusions are:

- The geothermal power plants to be installed have larger inertia than the power hydro plants they substitute. Therefore, the system is more likely to maintain stability under transient condition when the load is supplied from geothermal plants.
- When a large power demand is met with only geothermal power plants the system will be more stable than if it is met with hydro plants.
- When planning a new 250 MW aluminum smelter in northern Iceland where the power demand is met with both geothermal and hydro power plants we used a voltage stability study to determine the reinforcements needed to connect the load and the new plants to the transmission system.

7.5 Future Work

Other interesting questions arise for transmission operators when an increasing number of geothermal power plants are connected to the Icelandic transmission system. Next step would be to answer the following two questions:

- Should geothermal power plants take part in regulation and operation of the system, in the same way as hydro power plants?
- Is it possible to start-up an energy intensive factory, e.g. aluminum smelters, with only geothermal energy, i.e. a geothermal island?

To do so the model of the Icelandic transmission system has to be modified to enable long-term stability studies.

From the fact that no where else in the world is geothermal generation as large part of the total generation as in Iceland so some general conclusion can be drawn for other transmission systems.
8 References:


