IMPLEMENTATION OF ELECTRODE BOILERS FOR FREQUENCY CONTROL
OF UTILITY GRIDS

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IMPLEMENTATION OF ELECTRODE BOILERS FOR FREQUENCY CONTROL OF UTILITY GRIDS

A THESIS APPROVED FOR THE SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

BY
Dedication

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Dedication

I dedicate this thesis to my wife and my parents. Jeannie, your love, support and patience made it possible for me to pursue this degree.

Mom, dad, thank you for your continuous moral support and for believing in me.
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control of a high-voltage turbine being utilized for load-frequency control by actively adjusting the speed of the turbine itself as well as the water level control set-point and obtaining a faster boiler temperature.

The increased competition among the generation, such as wind-power, places greater emphasis upon the ability of the hydroelectric load-frequency control. A common method for load-frequency control is to maintain an automated generation plant with high-storage. This can also be achieved by assigning a necessary benefit of hot water storage. 

Various studies have shown that the current tools for load-frequency control do not account for water temperature fluctuations, production by and water level set-points. These power curves are parameterized in the model of operation and then set. This leads to the development of algorithms that account for boiler water temperature and dynamically modify the EMS curves to maintain the system behavior. The tested algorithm showed a clear improvement in maintaining load-frequency control, reducing the mean power output to 0.01%.
Abstract

This thesis successfully demonstrates an algorithm for improving the power control of a high-voltage electrode boiler being utilized for load-frequency control, by actively adjusting the slopes of XY-curves used for boiler water level control set-point and outputs as a function of boiler temperature.

The increase in transient energy co-generation, such as wind-power, places greater demands on an electrical grid for maintaining load-frequency control. A common method for load-frequency control used in Europe is decentralized co-generation plants with high-voltage electrode boilers. These provide a secondary benefit of hot water district consumer use.

Current high-voltage electrode boilers used for load-frequency control do not account for water temperature when determining conductivity and water-level set-points. Set-point curves are determined at the time of commissioning and then set. This thesis develops and tests an algorithm that accounts for boiler water temperature and dynamically adjusts the XY-curves that define the system behavior. The tested algorithm showed a clear improvement in maintaining load-frequency control, reducing the mean power error to 0 ± 0.5%.
Chapter 1: Introduction

This thesis successfully demonstrates an algorithm for adjusting level set-points and controller outputs for a high-voltage electrode boiler. These boilers are typically used as an electrical load in load-frequency control of the electrical distribution grid. The current control software does not include actual boiler temperature in the control algorithms causing an inaccuracy and deviation in the consumed power. The proposed algorithm improves the accuracy of the controller, consequently enhancing efficiency and lowering operational costs. The proposed algorithm is vital because growing renewable energy generation, specifically wind power, causes increased frequency deviations that cannot be adequately handled by traditional methods.

Wind energy is experiencing the most substantial growth of all sources of power generation. A status report from the global Renewable Energy Council (REN) [1] shows that wind power has had an annual growth rate of more than 20%. In many areas wind power is supplying as much as 20% of the total energy demand [2]. By the end of the year 2012 the total installed wind power capacity worldwide was more than 282 GW, 21% of this was generated in the United States (60 GW) [3]. Wind turbines, in particular variable-speed wind turbines, are very different from conventional thermal power generation, because they are not synchronous to the electrical frequency of the power distribution grid. Therefore, changes in load demand cannot adequately be opposed by inertia of the generator.
Mains frequency or grid frequency are synonyms for the frequency of electrical generation. The nominal frequency is 50 Hz for most of the world, but 60 Hz in the United States and the Northern parts of South America.

![Figure 1](image_url)  
**Figure 1** Typical Frequency Data over Period of One Hour

Figure 1 shows a graph depicting the system frequency during an hour with a 15 second resolution. The frequency is always changing and is determined by the balance between demand and supply. If demand is greater than generation the frequency will fall. Slight deviations of up to 100 mHz from the nominal frequency are very common, but it is critical to avoid deviations that exceed 200 mHz to secure the synchronous areas.

One of the main objectives of power system control is to actively counter frequency deviations in the distribution grid. Increasing the mechanical input to a synchronous generator will not directly increase the frequency, but will increase the power supplied by this generator. To achieve a balanced load versus generation ratio,
automatic load-frequency control is used. Load-frequency control consists of three phases, primary, secondary and tertiary. Some companies add a fourth phase called time control. The relation between the phases of load-frequency control is shown in Figure 2. The four types of mains frequency control implemented to help ensure deviations remain within tolerance [4]:

- **Primary Control** - Starts within seconds of deviation detection.
- **Secondary Control** - Replaces primary control over minutes.
- **Tertiary Control** - Partially complements and finally replaces secondary control.
- **Time Control** - Corrects global time deviations of the synchronous time in the long term.

![Figure 2 Control Scheme and Actions Starting with the System Frequency](Courtesy of UCTE OH)
The fundamental control problem with any power system is to match the power generation to the actual absorbed power (including net losses) [5]. Load frequency control is becoming more significant due to the increasing number and complexity of interconnected power systems. Smaller systems that are not interconnected with many loads and generators will not maintain frequency with the same degree of accuracy. In the past all transmission and generation facilities were owned by a single utility that would issue real power control signals to all of the generators within its network. Worldwide deregulation has decentralized and deregulated the structure of real power control. In Europe generation, transport and distribution are handled by different commercial entities. A solution to maintaining load-frequency control in a single grid operated by multiple suppliers, commonly used in Europe by the transport company, the company that ties up all generators and distributors, is accomplished by control algorithms issuing control signals to generators to adjust their output, or to distributors to adjust their consumption.

![Figure 3](image_url)  
**Figure 3** Traditional Centralized and Decentralized Generation
In Denmark, many companies have emerged that fill the role of both producer and consumer in the distribution net. Smaller co-generators and fast acting loads are used to actively perform load-frequency control close to the consumer. The difference in configuration is shown Figure 3.

Power production is achieved by these co-generators in the form of gas-engines and wind-turbines, while power consumption can occur by means of high-voltage boilers. The use of large loads for load-frequency control is a rather new concept in Denmark and even though the overall performance of this method is good, there are some volatility and precision issues. These issues are closely related to the fact that the power consumption changes as the temperature of the boiler changes.

This thesis evaluates an algorithm to actively adjust level set-points and controller outputs as a function of actual boiler temperature, in high-voltage electrode boilers that are used to perform load-frequency control of the grid. Chapter 2 presents background information on the electrical power grid and methods of load-frequency control. Furthermore the mechanical and electrical design of a typical electrode boiler are explored, with an in depth evaluation of the control systems used for operation. Chapter 3 develops the mathematical model relating changing power characteristics with change in temperature. An algorithm is proposed to improve boiler load accuracy by incorporating temperature-based control of level set-points. In chapter 4, the results of implementing and testing the algorithm in a live facility are discussed. Finally a conclusion is made and future research goals are proposed.
Chapter 2: Background

Electrical power consumption has been on a steady rise since Benjamin Franklin successfully researched the phenomena and sold his inventions in the 18th century. However, not until the late 19th century was real progress made thanks to research and inventions from numerous contributors [6]. Historically all energy was produced near the load requiring it; the first centralized element in modern energy industry was the production of gas. By the end of the 19th century, serious progress was being made on the expansion of the electrical power grid. Most of the early electric power used Direct Current (DC) and Edison devised the first power transmission system. Edison’s DC system generated and distributed electric power at the same voltage as was used by the consumers’ loads. This meant that the current in transmissions was rather large and conductors had to be large, further limiting the transmission distance. This forced the power companies to run different lines for different customer classes. Due to the large number of lines needed and inefficiencies of the transmission due to high current, the need to develop a distributed generation system arose [7]. In the modern Alternating Current (AC) system, distribution power can be transported more efficiently over larger distances. Transformers at both ends of the transmission are used to respectively raise and decrease the voltage levels. Generated power at generating stations is between 1 and 30 kV, while voltage levels commonly used for transmission of power range from 138 to 765 kV. Finally, the voltage is stepped down to accommodate consumers ranging from
120 V to 13 kV. Larger consumers are often directly supplied from the transportation net by means of dedicated transformers. See Figure 4 below.

![Color Key: Black: Generation Blue: Transmission Green: Distribution](image)

**Figure 4** Simplified Typical Electricity Grid

The increased voltage level and consequently decreased current level inherent in AC power systems, greatly reduces power loss in the transmission lines, which makes it possible to transport power over longer distances. With the realization of long distance power transportation, power companies interconnected local stations for the sake of load balancing and the improvement of the load factor. This is possible because larger grids offer the possibility of sharing power generation through different regions and diversification of loads. The load factor is defined by dividing the average load with the maximum load over a given time period. A high load factor indicates a constant power usage, while a low load factor shows an occasional high load demand. Interconnection of individual grids will balance the load better, resulting in a higher load factor. The electrification of the world further promoted this interconnection in the early 20th century and in the 1920’s United States utilities joined together.
2.1 Decentralized Electrical Power Generation

Historically, the generation of electrical energy was done in large centralized facilities often by means of natural gas, coal and nuclear or hydropower plants. Large facilities offer great advantages economically, but long transmission lines are needed, which can have a negative effect on the environment. The distribution grid became so large that the power companies could not guarantee cheap and reliable electricity to more remote consumers. Increasing the central generation was no longer enough to achieve better efficiency; however, better efficiency could be achieved by implementing smaller generating units collocated with the consumers.

A much-used decentralized generation method is cogeneration, which is the use of an engine to generate both electricity and heat used for heating applications. A typical lay-out of a co-generation grid is shown in Figure 5. The efficiency for generating electricity by means of a gas engine is often not more than 30 to 40%, but an increase to 90% or
higher is possible by means of heat recovery from the flue gasses emitted by the generator. Waste heat recovery is achieved by inserting a coil in the smoke stack through which water is circulated. The hot flue gas heats up the water that then can be used for heating purposes. Heat consumers are often industry, hospitals, green houses or district heating facilities. In a country like Denmark, 62% of households are connected to district heating [8], where many decentralized facilities supply both thermal energy and electricity. Decentralized cogeneration is considered to have vast environmental and economic advantages [9].

Another method of decentralized generation is to use wind power to generate power with wind turbines; it is a method that was used for thousands of years, but became obsolete after the industrial revolution. In the early 1970’s, during the first oil price shock, wind power generation made a comeback as a reliable and consistent power source by using other sources as back up [10]. Wind turbines have minimal maintenance and the only pollution associated with this kind of generation is during manufacturing and maintenance. The problem with wind power is that it is usually intermittent causing uncertain power availability and possible frequency deviations in the grid [11].

Not only the number of installations is rapidly increasing, but also the capacity per installation has increased immensely [12]. In the 1980’s 300 kW turbines were state of the art; by the time of writing in 2014 an 8 MW turbine has been deployed by the Danish company Vestas [13]. The increase in number of units and capacity per unit, has significantly affected the variation in load-frequency.
2.2 Load Frequency Control

The quickly increasing number of wind turbines in the grid will result in a decreasing number of conventional power plants requiring new methods of load-frequency control, the controlling of real power output of generating units in response to changes in system frequency within specified limits. To maintain a stable grid frequency is important for numerous time dependent devices such as:

- Tariff meters of electrical energy.
- Power plant control energy.
- Power quality devices.
- Synchronous motors.

Load frequency control is part of the automatic generation control system and is critical in the operation of power systems and is organized in three or four levels [14] [15]. The four levels consist of primary, secondary and tertiary control, and optionally time control.

2.2.1 Primary Control

The controllers of the generating units perform the primary control. The first phase relies on the release and absorption of kinetic energy by the rotor of the synchronous generators, resulting in a change of frequency. Consequently, active controllers change the input to the generators. Since the generators inside wind turbines are much smaller than conventional synchronous generators, the inertia contribution of
these turbines is much smaller. Transients of primary control are usually in the scale of
seconds. If the deviation from the nominal frequency exceeds ±20 mHz in the Continental
European model, primary control is activated. This number is derived from the sum of
the allowable measurement error of 10 mHz and a 10 mHz dead zone of the controller.
The primary control is proportionally activated from 0% to 100% when the deviation is
±20 mHz to ±200 mHz. While long-term (30 second) deviations of maximum ±180 mHz
are permissible, short-term (seconds) deviations of up to ±200 mHz are allowed.
Maximum activation of the generator occurs in the event of a frequency deviation of 200
mHz or more. Maximum activation has to be reached within 30 seconds of the frequency
deviation. It must remain available for at least 30 minutes. Primary control is not able to
return frequency to normal levels, it can only stabilize it. The other control components
are used to restore frequency levels [16].

2.2.2 Secondary Control

The next phase, secondary load frequency control, consists changing the set-point
of the engine feeding the generator, causing the frequency to be brought back to its
nominal value. Secondary load-frequency control is used to restore frequency to its
scheduled value, following a disturbance. The time associated with this type of control
ranges from one to ten minutes.

2.2.3 Tertiary Control

The third phase is called tertiary control, also referred to as “minutes reserve.” It
is activated when the deviation in the control area lasts for longer extents of time (10 to
30 minutes) and is used to relieve secondary control, so that it can be implemented again. Secondary control should be available at all times to ensure correct load-frequency control. Tertiary control consists of actions taken to get additional resources in place to handle current and future incidents.

2.2.4 Time Control

The last phase is time control. Because load-frequency control and balancing are not perfect, there will always be small deviations in net frequency. Time control is used to maintain the long term average frequency at its scheduled value (50/60 Hz). If average frequency drifts, it creates a time error in the net. If for example the average frequency over a day has been running high, a clock using the frequency will gain several seconds. All balancing authorities will decrease the scheduled frequency by a small margin until the average frequency is restored to normal. To determine the actual frequency the Coordinated Universal Time (UTC) is used. The electrical time of the synchronous area is determined by the integration of the frequency / voltage time period.

2.3 Regulation Reserves

Alternative energy sources are in the spotlight and are experiencing an immense growth rate. The integration of these renewable energy sources with the existing load-frequency control is very challenging. The energy sources are mostly connected to the grid through electronic power converters, and no inertial response can be provided as feedback for load frequency control [17]. Instead of using a generating capacity for
primary load-frequency control, a load can be used. This load has to be able to change
power consumption relatively fast from low load to full load in less than 30 seconds, and
vice versa. There are three distinct areas of use: 1) Primary or secondary control to
increase the generation capacity or decrease power demand (regulate up reserves); 2)
decrease the generation capacity or increase power demand (regulate down reserves); or
3) a combination to facilitate both (combined control). These types of load-frequency
control can be very attractive when the prices for electricity are low, because to use a
high-voltage electrode boiler a certain power capacity has to be purchased. When prices
are low, the boiler can be used to produce thermal energy at a very low cost. When prices
are high, electrical power generated by means of co-generation can be sold to the operator
and the thermal energy that is a by-product of this form of generation can be sold to the
consumer. In Northern Europe, an electricity exchange has come to life. This exchange
gives potential consumers and contributors the opportunity to buy or sell electrical
capacity in certain periods. Northern Europe is largely dependent on hydro and wind
power. Periods of little precipitation or wind can cause a deficiency in power generation.
When there is still power demand, prices increase and it becomes very lucrative to sell
capacity. However, when demand is very low or there is an abundance in hydro or wind
power, it can be very efficient to buy capacity. Many district heating facilities in Northern
Europe cogenerate electricity and thermal energy. When power demand is low, but there
is a demand for heat, heat generation is usually performed by gas-fired boilers. However,
when the cost to generate heat-using electricity is lower or even negative as highlighted
in Figure 6, this becomes a very lucrative possibility.
2.3.1 Regulate Up Reserve

Regulate Up reserve consists of a fast acting generation that can ramp up quickly to increase the net frequency. Alternatively, a considerable high load that can decrease quickly can be implemented. Using loads to regulate up reserves has not been in high demand because a high load often translates to a high cost. It is very common to use co-generation for up-control. However, when there is urgent need for up regulation, and electricity prices are very low, it can be advantageous to use this solution. As can be seen in Figure 6 above, a negative price is possible. This means that one will receive money to absorb power. Although it rarely occurs, prices of about $200.00/MWh have been recorded [18]. The proprietor will buy, or get paid to absorb a certain amount of capacity,
and report the load for operation. Now the grid-manager will automatically decrease the load when the net frequency falls.

2.3.2 Regulate Down Reserve

Regulate Down reserve is the exact opposite of the up-control and is very attractive for operators. Usually it consists of generators that can decrease generation. Alternatively a controllable load resource can be used that can quickly increase load. Either solution can be reported in for duty and power can be purchased or sold for operation.

2.3.3 Combined Control

Combined control is a combination of regulate-up-and-down control, to both increase and decrease the grid frequency. This type of control is not very common for operators that solely rely on either generation or consumption; but for those operators that employ both solutions, this could be a very attractive way to generate heat at a very low cost.

2.3 Effects of Wind Turbines

The quickly increasing number of wind turbines in the grid will result in a decreasing number of conventional power plants, requiring new methods of load-frequency control. Primary frequency control with wind turbines is more difficult than conventional generators due to the lack of inertial feedback caused by the smaller generator size. Often wind turbines are coupled to other forms of generation that can
provide back up and primary control [19]. To be able to use the control reserves of these back-up generators, they have to be active in the net [20]. The Electrical Power Processing unit of Delft University of Technology in the Netherlands proposes a combination of wind turbines and fuel cells in a paper from 2006 [21]. In this model the fuel-cells are used as a back-up for power generation and as a source of load-frequency control. Fuel cells directly convert fuel and an oxidant into electricity, achieving higher efficiencies than conventional internal combustion engines [22]. There are several types of fuel cells, distinguished by the oxidant used. Solid Oxide Fuel Cells operate at a high temperature (700 to 1000 °C) and offer the possibility of co-generation to produce additional power through thermal energy. The solution proposed in [21] is demonstrated with two time-domain simulations. The paper concludes that in interconnected power systems the inertia will be larger, causing the change of frequency to be smaller. Smaller systems, particularly in low load situations and during high wind speeds, might experience more volatility. Time-domain simulations show that it is very feasible to have a combination of fuel-cells and wind-turbines supporting each other [21]. In case of frequency droops, the rotating mass of the wind-turbine can be used to support the primary frequency for a short period, thus allowing time for the fuel-cell to respond.
Chapter 3: High-Voltage Electrode Boilers

An alternative to the implementation of fuel cells or other forms of generation in combination with wind turbines is to install fast responding loads. A rather new load that has been implemented is the high-voltage electrode boiler. The concept of an electrode boiler is simple; it is a boiler that passes an electric current through electrodes immersed in a liquid. The liquid acts as a resistive medium that completes the circuit between the electrodes.

The resistance of said liquid converts the electric current into thermal energy. It depends on the same concept as electric arc furnaces used to produce aluminum, first patented in 1878 by Sir William Siemens. In this thesis one specific type of electrode boiler is
evaluated, the PARAT IEH from the Norwegian boiler manufacturer PARAT Halvorsen AS, (see Figure 7). PARAT has been manufacturing and installing electrode boilers for several decades. From 2006, an alliance began with the Danish company, AS Scan, and the first electrode boiler for primary frequency load control was commissioned. As of March 2014, seven boilers are operational in Denmark and six more boilers are being commissioned in Germany. There are two distinct methods of using the thermal energy from an electrode- boiler, either in the form of hot water or steam. All of the Danish boilers are implemented as hot water boilers, while the German boilers are operated as steam boilers as can be seen in Figure 8 and Figure 9.

In a steam boiler, shown in Figure 8, thermal energy is extracted in the form of steam from the top of the boiler and the circulation circuit is a closed loop. Processed feed water
maintains nominal water levels in the boiler based on feedback from the water level control circuit. An automatic blow down system removes any sediments from the bottom of the boiler which can cause increases in conductivity of the water.

Figure 9 shows a typical hot water boiler. The main difference is that the thermal energy is extracted by means of a heat exchanger, such that the liquid in the internal circulation loop is not actually extracted from the boiler. The circulation pump for a hot water boiler is significantly larger to ensure that sufficient energy is delivered to the heat exchanger. In this boiler the processed feed water controller remains relatively inactive because no water is extracted from the boiler. Under normal circumstances, boiler conductivity is constant so no sediments are to be removed from the bottom of the boiler. The boiler is pressurized with nitrogen; this removes all oxygen and hydrogen from the boiler.
Excessive oxygen can cause corrosion in the boiler, circulation lines and heat exchanger. Corrosion can cause leaks and the efficiency of a heat exchanger affected by rust will fall significantly. Small amounts of hydrogen are produced when the boiler is in operation, and the pressurized nitrogen forces the hydrogen to collect in the top of the boiler, from where it is vented to the atmosphere using a time controlled air valve.

3.1 Mechanics

One of the great advantages of an electrode boiler is the simple construction. The PARAT IEH consists of an outer vessel with an additional inner container. A pump circulates liquid from the bottom of the outer vessel to the inner container. This inner container holds the liquid in which three or six electrodes are submerged. Figure 10 depicts a typical electrode, which consists of several parts; including a carbon steel rod to which a mounting piece is attached. The mounting piece holds twelve cast iron electrode rods arranged in a circular pattern, with an additional central electrode rod. The electrode sets are mounted inside the boiler in a circular fashion such that the distance between each neighboring electrode is equal.
Throughout the inner container, 18 to 36 neutral electrodes are situated around the main electrodes, see Figure 11.

The neutral electrodes are directly bolted to the inner container. These electrodes were developed in collaboration between PARAT Halvorsen and “Norges teknisk-naturvitenskapelige universitet” (NTNU). NTNU is the Norwegian University of Science and Technology. Through implementing neutral electrodes, PARAT and NTNU were able to reduce the electrode wear significantly. Traditional electrode boilers, not using neutral electrodes, that are in operation more than 4000 hours a year, especially when operating around low loads, show significant signs of wear on the electrodes. Worn down electrodes have to be replaced annually to avoid asymmetric current flow through the active electrodes.

3.2 Electrical

The typical operating voltage of a PARAT IEH is between 10,000 and 11,500 VAC arranged in three phases. Operated in land-based installations, the load is perfectly symmetrical. Each of the electrodes, be it three or six, are submersed equally. Because of
this balanced load, there is no need for a neutral conductor. As such, the inner container is electrically isolated from the outer vessel by TEFLON® isolators. TEFLON® has an extremely high resistance at grid frequencies, so the inner container functions as an isolated neutral.

This type of boiler has also been successfully implemented on a floating production, storage and offloading (FPSO) vessel in the Gulf of Mexico, owned and operated by BW Offshore for Petrobras America. This offshore version of the electrode boiler is equipped with six electrodes. The two electrodes for each phase are deployed opposite each other, so during sway and surge motions of the vessel, each phase is still submerged equally. The inner container and the electrode are also over-dimensioned to allow for more sway and surge. An obvious limitation is a theoretical maximum allowable sway and surge, which is actually set to 14° in all directions. This application has been successfully patented by PARAT, and PARAT is still the only company in the world to have implemented such a solution.

As previously mentioned, the improved performance from the use of neutral electrodes comes from the fact that the neutral electrodes ensure the sum of the currents is zero at all times. Before the neutral electrodes were suggested, the wear down of electrodes could result in an imbalance of load, which again could result in a residual neutral current. There are other situations that could result in a residual neutral current, the obvious situation being the loss of one or two phases. A main circuit breaker is
employed to engage and disengage the boiler on demand and secures the maximum current drawn by the boiler. The main breaker would also disengage with a loss of phases.

3.3 Control System

The control system for the PARAT IEH consists of a SIEMENS S7 300 Programmable Logic Controller with a Beijer Electronics iX Human Machine Interface. In Figure 12 a typical control cabinet as supplied by PARAT Halvorsen AS. The conventional electrode boiler as delivered by PARAT has been controlled by PLC for 20 years. The PLC program for these electrode boilers was rewritten in 2007 and significantly revised in 2009. The control philosophy for a conventional hot water PARAT IEH boiler consists of many components each with its own dedicated controller.

![Typical PLC Control Cabinet](image)
The following components are part of the PARAT IEH boiler control philosophy:

- **Power Controller** - Ensures actual absorbed power is equal to the external power set-point that ensures proper load-frequency control by altering the upper water level set-point.

- **Boiler Supply Temperature/Pressure Controller** - Ensures temperature or pressure is sufficiently high for use by the consumer, but is within boiler specifications. This is achieved by limiting the output from the power controller.

- **Upper Level Controller** - Ensures actual upper water level is equal to the set-point from the power controller. The water level is altered by raising and lowering the overflow pipe in the inner container.

- **Total Level Controller** - Ensures the total boiler level, which is the total volume in both the outer vessel and the inner container, is sufficient for operation. For steam applications this is done with a continuous controller altering the speed of a feed-water pump, while for hot-water applications only make-up water is added to account for any water losses due to bottom blow down.

- **Pressure Controller** – For use in a hot-water boiler. Ensures boiler pressure is high enough to achieve needed temperature but is within boiler specifications. To achieve temperatures over 100 °C the boiler needs to be pressurized to avoid the water from boiling and steam production.
• Conductivity Controller - Ensures conductivity of the boiler water is within operational limits. High conductivity may cause overshoots of power or even arcing; low conductivity will cause decrease of power capacity.

• Secondary Temperature Controller – For use in hot-water systems. Ensures temperature delivered to secondary water distribution network is high enough for the consumer, while assuring enough energy is consumed from boiler.

The following sections discuss each controller in depth.

3.3.1 Power controller

In conventional electrode boilers, the power controller is only used to limit the absorbed power while maintaining boiler pressure or temperature set-points. In the PARAT IEH system, when it is used for load-frequency control, the power controller is the master of a cascaded controller. The cascaded sequence is shown in Figure 13. The slave of this controller is the upper water level controller.

![Cascaded Power Level Controller](image)

Figure 13 Cascaded Power Level Controller
The power controller receives an external set-point from the load-frequency controller and has two basic modes of operation: normal operation and load-frequency control. In normal mode, the controller works as a regular proportional-integral-derivative (PID) controller and tries to get the absorbed power to reach the set-point as quickly and smoothly as possible. Depending on the current electrical grid situation, this set-point can be very volatile and change from 0% load to 100% load in a single cycle (100 ms). When the boiler is being utilized for primary load-frequency control, the actual absorbed power has to reach the new set-point within 30 seconds of the set-point change. It is also possible that the boiler is used for secondary control. During secondary control, the power controller will smooth out the change in set-point such that the change per second does not increase beyond certain limits. These limits are specified by the grid-manager and are usually the maximum power divided by 150 seconds. For a 10 MW boiler this means a maximum change of 67 kW a second.

Primary control is automatically activated when the change from one cycle to the next exceeds a percentage set by the operator. When activated, it locks the power and the level controller and sets the controller outputs to a preset position that corresponds with the set-point for power. This means that the upper water level set-point is locked and the overflow pipe is forced to a fixed position. This position is derived from an XY-curve that is set during commissioning. This XY-curve is close to linear, but after extended operation the boiler water conductivity changes slightly, causing the system behavior to drift from the initial curve. Conductance also changes with temperature. The normal
operation temperature should not change too much, but the actual temperature around the electrodes is expected to fluctuate more aggressively.

The minimum output from the power controller is limited by an operator set-point. If the level in the upper container becomes too low, the electrodes will no longer be submerged in water. A gap will form between the electrodes and the water, causing an open loop between the electrodes and possible load imbalances. If the gap is relatively small, less than 3 mm, there is a chance that sparks will form between the electrode tips and the surface of the water. There is a theoretical possibility that if the time-controlled hydrogen relief fails and a hydrogen bubble is formed in the top of the boiler, the hydrogen may be ignited by the sparks.

The maximum output is limited by an additional XY-curve. The curve is similar to the set-point curve; it is designed to prohibit the absorbed power from overshooting the set-point. The main circuit breaker is often set to trip at 105 or 110% of the rated boiler power. If the actual power absorbed by the boiler exceeds these set-points and a trip occurs, the load will fall from the electrical grid, which can have detrimental effects to the frequency of the grid.

3.3.2 Boiler Supply Temperature / Pressure Controller

If the boiler is implemented as a hot water boiler, the secondary loop for the cascaded controller is the boiler supply temperature. The boiler supply temperature is measured directly after the outlet of the boiler, upstream of the main circulation pump.
For steam boilers, the secondary loop is the boiler pressure. In conventional industrial applications, this temperature or pressure would be the primary control loop for the cascaded boiler control; however, in load-frequency control, the temperature or pressure controller is only used to limit the manipulated output from the power controller. The absorbed power has high priority, but in case of a boiler temperature or pressure that approaches the design limits of the boiler, the power controller will be limited to ensure a decrease in temperature or pressure. If limiting the power controller does not decrease temperature or pressure and it rises over the maximum working set-point, the boiler will automatically disengage the main circuit breaker. The breaker re-engages when the boiler temperature or pressure has sufficiently decreased. Under normal operation, it is very undesirable that the temperature/pressure controller limits the power controller, which can be avoided by ensuring that the boiler can dump all thermal energy it generates to the consumer grid.

In case a critical failure occurs and multiple safety devices fail, without the boiler ceasing operation, pressure can build inside the boiler. To ensure that the boiler pressure will never exceed the boiler design specifications, multiple pressure safety valves are fitted on the boiler. Each of these valves can dump the amount of steam that the boiler is theoretically able to produce.

3.3.3 Upper Level Controller

The upper water level controller is the slave in the cascaded control loop and receives its set-point from the power controller. A drainpipe is mounted in the center of
the inner container, the height of which is manipulated, causing the level to increase and decrease proportionally with the position of the drainpipe. When the current water level is lower than the set-point, the circulation will be ramped up to ensure enough water is pumped from the outer vessel to the inner container. The drainpipe diameter is designed such that the actual boiler level is drained with very little delay time. The minimum and maximum controller outputs are limited such that the water level cannot fall to low, causing arcing, or go too high causing power overshoot.

The first revision of the control system for implementing load-frequency control was made in 2010 and has since undergone continuous improvements. The major change between the conventional control program and the load control program is a series of six XY-curves that are predetermined at the time the system is commissioned. The first curve is used to limit the level set-point that comes from the power and temperature controllers according to the load demand. The second curve is similar, but limits the output from the water level controller. A third curve is used to preset the water level controller output with changes in load demand that are greater than 25%. The fourth curve is used to set the speed of the primary circulation pump according to the power currently absorbed by the boiler. When the boiler is in low load, the water level in the container is very low. If the circulation pump is running at a high speed water can spray on the electrodes. To ensure sufficient circulation to deliver as much thermal energy as possible to the consumer network during higher boiler loads, the speed of the circulation pump is increased. The fifth curve reduces the set-point for the return temperature into the boiler with higher boiler loads. This is to ensure enough thermal energy can be absorbed by the
water without causing a temperature shut-down and low secondary temperatures during low loads. The last curve controls the opening of the shut off valve on the secondary side of the heat exchanger to control the flow through the consumer network. This is to ensure the temperature to the consumer accumulation tanks is consistent. Low temperatures cause imbalance in the tanks, effectively decreasing the thermal capacity. High temperatures can cause shut-downs and damage to the equipment.

3.3.4 Total Level Controller

The total level is calculated by adding the active water volume of the upper and lower containers. The active volume is determined by the container diameter and the active control height, which is limited by the nozzle placement of the water level gauges. When water is barely visible in the bottom of the level gauge, the water level indicated by the level transmitter is 0%. When the water level is in the top of the level gauge, the indicated level is 100%. The level gauge has an active length of about 1000 mm. The container diameter depends on the rated boiler capacity. For a 20 MW boiler utilizing six electrodes, the outer shell has a diameter of 2350 mm and the inner water container has a diameter of 1940 mm. For the water volume to be accurate, the volume of the electrodes has to be subtracted from the equation. Each electrode has a volume of 0.066 m$^3$. With this data, the total water volume can be determined:
Using the ratio between the lower and upper water volume, the total water level noted as a percentage is calculated:

\[
L_{\text{total}} = \frac{V_{\text{lower}}}{V_{\text{total}}} L_{\text{lower}} + \frac{V_{\text{upper}} - V_{\text{electrodes}}}{V_{\text{total}}} L_{\text{upper}}
\]

\[
= \frac{4.34}{6.91} L_{\text{lower}} + \frac{2.57}{6.91} L_{\text{upper}}
\]

\[
= 62.8\% \cdot L_{\text{lower}} + 37.2\% \cdot L_{\text{upper}}
\]

For a PARAT IEH system implemented as a steam boiler, a continuous total water level is essential, because large quantities of water are extracted in the form of steam. A steam boiler is fitted with one or more feed-water pumps with speed control or feed-water pumps combined with control valves. To ensure optimal operation, the total water level should be as high as possible. The maximum level is determined by the water level in the lower container, which cannot exceed a water level of 95% at any time. When there is no operation of the circulation pump, all water will collect in the lower container. If the lower water level exceeds 95%, a boiler shut-down is initiated to prevent the possibility of a
short-circuit of the outer shell and inner container through the water. Using the formula derived, we get a maximum total water level of:

\[ L_{\text{total}} < 62.8\% \cdot L_{\text{lower}} \]
\[ < 62.8\% \cdot 95\% \]
\[ < 59.7\% \]

To allow for additional pre-alarm limits and small deviations of the set-point, the actual set-point should be set around 55%.

When a PARAT IEH system is used as a hot-water system, no water is extracted from the boiler, other than small amounts of water that are expelled from the boiler by the bottom blow down process. To ensure a sufficient total water level, a single make-up water pump is used with a simple start/stop logic. Start and stop levels typically are around 50% and 55% respectively.

Regardless of the type of implementation, a boiler shut-down will be initiated when the water level in the lower container comes under 5%. A water level that low can cause air to be sucked in to the circulation pump, which can cause a stall in circulation or damage to the pump. When the lower water level becomes too low, the circulation pump is stopped and a shut-down is initiated.
3.3.5 Pressure Controller

An electrode boiler implemented as a hot-water boiler is pressurized by means of nitrogen. Pressurizing is performed to increase the temperature range of the boiler. At atmospheric pressure, the boiling point for water is approximately 100 °C.

![Graph of Boiling Temperature vs. Absolute Pressure](image)

**Figure 14** Boiling Temperature vs. Absolute Pressure

The maximum rated temperature for a typical hot-water boiler is 115 °C. To be able to reach this temperature, an absolute pressure of at least 1.65 bar is needed, as shown in Figure 14.

Typically, the boiler is pressurized to about 2 bar relative pressure, which corresponds to about 3 bar absolute pressure. Pressurizing is done by means of nitrogen,
because of its inert properties. It suppresses the forming of sparks, and forces oxygen and hydrogen to the top of the boiler from where they can be expelled by means of a pressure relief valve. The pressure relief valve is time controlled, and typically opens for two seconds after 8 hours of operation.

3.3.6 Conductivity Controller

The operation of any electrode boiler is based on the conversion of an electrical current through the resistance, or conductance, of water. During commissioning, caustic soda (NaOH) is added until the conductivity of the water is sufficient for the boiler to reach its rated power. During operation the conductivity of water may increase due to sediment and impurities in the boiler. For hot-water systems, which operate in a closed loop, this may not be very significant, but for a steam system to which considerable amounts of new feed-water are introduced this may become a bigger issue. To counter this increase in conductivity, a bottom blow valve is fitted. For a hot-water boiler this is a solenoid valve that opens for a few seconds when the conductivity of the boiler water exceeds a set-point. After a blow-down, a stabilizing timer is started to allow for the boiler conductivity to settle. The blow-down will result in a drop of the water level, which will cause the make-up pump to start, adding new water with a very low conductivity (see section 2.5.9). Two or more blow-down cycles may be needed for the water level to sink sufficiently to get below the make-up pump start limit.

A steam boiler is fitted with a continuous blow-down valve, manipulated by a PID-controller. One of the effects of extracting steam and introducing large amounts of
feed-water to a boiler is the increase in conductivity. Even though feed-water has a low conductivity, the continuous extracting of water in the form of steam causes minerals and impurities to settle. This makes a continuous bottom blow-down necessary.

3.3.7  Return Temperature Controller

A return temperature transmitter is fitted in the return line from the heat-exchanger to the boiler. The return temperature is determined by the amount of thermal energy that is delivered to the secondary consumer network through the heat-exchanger. This amount of energy is determined by the volume of water that is pumped through the heat-exchanger, and is controlled by adjusting a set of butterfly-valves interconnected to function as a three-way control valve. The temperature set-point is adjusted by an XY-curve as a function of the current power generated by the boiler. A lower power generation will result in a higher set-point to achieve a sufficiently high supply temperature such that the temperature in the secondary consumer network can be guaranteed. At higher boiler loads, the set-point is lowered to allow for an increased thermal energy buffer in the water.

3.3.8  Secondary Supply Temperature Controller

The secondary supply temperature is the temperature measured after the heat-exchanger on the secondary consumer grid. When the boiler is in operation and the three-way control valve mentioned in the previous section is opened, a shut-off valve will open proportionally with the opening of the three-way control valve. The proportion is determined by an XY-curve and is set during commissioning, such that the secondary
supply temperature does not fall too low. When the shut-off valve is opened, the secondary circulation pump is started; a larger opening of the valve will automatically result in an increased volume of circulated water. The secondary circulation pump is frequency controlled and a PID-controller is implemented to ensure the secondary supply temperature does not exceed the set-point too much.

3.3.9 Feed-Water / Make-Up Water Supply

A key parameter that determines the power consumption of an electrode boiler is the conductivity of the water. To ensure correct operation of the boiler, it is essential that the feed-water, or make-up water, entering the boiler has a very low conductivity. To ensure sufficient low conductivity, the water is treated by a series of filters.

The first stage of the water treatment system is a simple cartridge filter that removes solids and bigger impurities like sand or rust particles. The next stage consists of a softening filter that softens the water. A softening filter is filled with small beads that are negatively charged and bonded to positively charged sodium ions. When water flows through the filter, the calcium and magnesium ions swap places with the sodium. A reverse osmosis filter consequently demineralizes the softened water. “Osmosis is the passage or diffusion of water or other solvents through a semipermeable membrane that blocks the passage of dissolved solutes [23]” For a reverse osmosis application the unfiltered water is pressurized causing the water molecules to pass through the membrane while salt molecules remain in the ‘dirty’ side of the filter. The resulting water is between 1 and 20 μS in conductivity. Constant monitoring of the conductivity is performed by a
conductivity analyzer, which is situated in the circulation stream. The process value from
the analyzer is temperature compensated and shows the conductivity for 25 °C.

For hot water applications, the boiler is filled and an initial startup is performed.
Because of corrosion and other impurities in the boiler, the conductivity will likely rise.
The goal during commissioning is to achieve the rated power consumption of the boiler
with a level that is just under 100%. If the power consumption is at the boiler rating, the
water in the boiler has to be purged with low conductivity water. In most cases the
conductivity will be too low and caustic soda (NaOH) is added to increase it. When the
conductivity of a hot water boiler is adequate, generally no new water or caustic soda has
to be added until the boiler is drained.

For steam boilers, there is a need for constant feed water supply. In the majority
of the applications, this feed water comes in the form of return condensate from the
consuming process; but in some cases all or part of the steam is consumed during the
process. Depending on the size of the boiler, large scale reverse osmosis filters are needed
to supply enough feed water.
Chapter 4: Methods

As mentioned in previous sections, the correct operation of an electrode boiler is largely dependent on the conductivity of the water. Deviations of set-points and inaccuracy of the controllers are caused by the changes of the boiler water conductivity. Increased conductivity caused by sediments and other contamination of the water are sufficiently handled the conductivity controller, but changes caused by temperature swings have never been investigated. To understand these changes in conductivity, mathematical analysis is necessary.

4.1 Analysis

One obvious concern associated with the operation of high-voltage electrode boilers is the chance of personal or material damage because of direct exposure to the high-voltage. For information purposes, a hypothetical case is presented to calculate the current to ground.

In case of destructive failure, the maximal achievable voltage from one phase to ground is given by:

\[ V_{L-GND} = \frac{V_L}{\sqrt{3}} \]

\[ = \frac{11,500}{\sqrt{3}} \]

\[ = 6,640 \, V \]

where \( V_L \) is the line voltage.
The resistance consists of the volume of the water and the electrolytic conductivity or specific conductance of this liquid.

The major paths of conduction are the circulation and drain pipes, as shown in Figure 15. The pipes are constructed from TEFLON®, which is a material with immense dielectric properties at line frequencies; therefore the conductivity of this material can be neglected. The conductivity of liquid is temperature dependent. For the following calculations, the worst-case situation is used where the conductivity exceeds the design parameters. The maximal achievable temperature that does not result in a shutdown is 204 °C for a steam boiler, and 115 °C for a hot water boiler. Similarly, the maximal allowable conductivity of the water at room temperature (25°C) is determined to be 28 \( \mu S \) for a steam boiler and 60 \( \mu S \) for a hot water boiler. The conductivity is a very important
part of the boiler operation, and is explored in-depth in Chapter 5. Resistance calculations in case of a destructive short-circuit are in the following section.

4.1.1 Resistance Calculation Steam Boiler

- Conductivity \( \sigma (\mu S) \) of liquid (H\(_2\)O) as a function of temperature \( T (\degree C) \)

\[
\sigma_{25 \degree C} = 28 \mu S \frac{S}{cm}
\]

\( T = 204 \degree C \)

\[
\sigma = \sigma_{25 \degree C} \cdot (1 + 0.02(T - 25))
\]

\[
= 28 \cdot (1 + 0.02(204 - 25))
\]

\[
= 128.2 \mu S \frac{S}{cm}
\]

- Resistance \( R (\Omega) \) in each of six circulating pipes with inner diameter \( d = 80 \) cm and length \( L = 170 \) cm

\[
A = \pi \cdot \left(\frac{d}{2}\right)^2
\]

\[
= \pi \cdot \left(\frac{8}{2}\right)^2
\]

\[
= 50.27 cm^2
\]

\[
R_{CIRC} = \frac{L}{\sigma \cdot A} = \frac{170}{128.2 \cdot 10^{-6} \cdot 50.27}
\]

\[
= 26,370 \Omega
\]
• Resistance $R$ (Ω) in drain pipe with inner diameter $d = 2$ cm and length $L = 70$ cm

$$A = \pi \cdot \left(\frac{d}{2}\right)^2$$

$$= \pi \cdot \left(\frac{2}{2}\right)^2$$

$$= 3.14 cm^2$$

$$R_{DRAIN} = \frac{L}{\sigma \cdot A}$$

$$= \frac{70}{128.2 \cdot 10^{-6} \cdot 3.14}$$

$$= 173,750 \Omega$$

• Total Resistance $R$ (Ω) in six circulation pipes and drain pipe

$$R_{TOT} = \frac{1}{\frac{6}{R_{CIRC}} + \frac{1}{R_{DRAIN}}}$$

$$= \frac{1}{\frac{6}{26,370} + \frac{1}{173,750}}$$

$$= 4,286 \Omega$$

Combining this data results in a worst-case ground current for an electrode boiler operated as steam boiler:
\[ I_{GND} = \frac{V_{L-GND}}{R_{TOT}} \]
\[ = \frac{6,640}{2,136} \]
\[ = 1.55A \]

4.1.2 Resistance Calculation Hot Water Boiler

- Conductivity \( \sigma \) (\( \mu \text{S} \)) of liquid (H₂O) as function of temperature \( T \) (°C)

\[ \sigma_{25\degree C} = 60 \frac{\mu}{\text{cm}} \]
\[ T = 115 \degree C \]
\[ \sigma = \sigma_{25\degree C} \cdot (1 + 0.02(T - 25)) \]
\[ = 60 \cdot (1 + 0.02(115 - 25)) \]
\[ = 168 \frac{\mu}{\text{cm}} \]

- Resistance \( R \) (Ω) in each of six circulating pipes with inner diameter \( d = 80 \text{ cm} \) and length \( L = 170 \text{ cm} \)

\[ A = \pi \cdot \left(\frac{d}{2}\right)^2 \]
\[ = \pi \cdot \left(\frac{8}{2}\right)^2 \]
\[ = 50.27 \text{cm}^2 \]
\[ R_{CIRC} = \frac{L}{\sigma \cdot A} \]

\[ = \frac{170}{168 \cdot 10^{-6} \cdot 50.27} \]

\[ = 20,129 \Omega \]

- Resistance \( R \) (\( \Omega \)) in drain pipe with inner diameter \( d = 2 \text{ cm} \) and length \( L \)

\[ = 70 \text{ cm} \]

\[ A = \pi \cdot \left( \frac{d}{2} \right)^2 \]

\[ = \pi \cdot \left( \frac{2}{2} \right)^2 \]

\[ = 3.14 \text{ cm}^2 \]

\[ R_{DRAIN} = \frac{L}{\sigma \cdot A} \]

\[ = \frac{70}{168 \cdot 10^{-6} \cdot 3.14} \]

\[ = 132,629 \Omega \]

- Total Resistance \( R \) (\( \Omega \)) in six circulation pipes and drain pipe
\[ R_{TOT} = \frac{1}{6} \frac{1}{R_{CIRC}} + \frac{1}{R_{DRAIN}} \]

\[ = \frac{1}{6} \frac{1}{20,129} + \frac{1}{132,629} \]

\[ = 3,272 \Omega \]

Combining this data results in a worst-case ground current:

\[ I_{GND} = \frac{V_{L-GND}}{R_{TOT}} \]

\[ = \frac{6,640}{3,272} \]

\[ = 2.0A \]

### 4.2 Temperature Compensation

As shown in the previous equations, the electrical conductivity of all solutions changes as temperature changes; a higher temperature results in a higher conductivity. For every degree of temperature increase, the conductivity increase is about 2% [24]. Most specialized conductivity analyzers available on the market are equipped with active temperature compensation, and the value used for logging and controls is the conductivity at room temperature [25 °C]. Having an active temperature compensation ensures periodic measurements are consistent and can be compared regardless of actual sample temperature.
For the application of water measurements in electrode boilers, consistency is very important to ensure that the NaOH added to the boiler is not increasing the conductivity too much. The increase in conductivity of the water is very rapid, when NaOH with a very low concentration (0.2%) is added. A teaspoon of NaOH solution can increase the conductivity of the entire boiler volume by several µS. The average conductivity of the PARAT IEH, when operated as a hot water boiler, is 60 µS, at 25 °C. When an electrode boiler is being implemented for load-frequency control, the actual load of the boiler can quickly fluctuate from 0% to 100%. Because of these fluctuations, the temperature of a hot water boiler in operation can be between 80 °C and 115 °C. The actual working temperature should not fall below 90 °C, or exceed 110 °C. This translates to an actual conductivity that fluctuates from 132 µS to about 152 µS, as shown in Figure 16. It should be noted that the change in conductivity is linear over the temperature ranges considered in this thesis. The fluctuation in conductivity causes problems in the linearity between the water level around the electrodes and the absorbed power. To counter these fluctuations and to improve the speed and the accuracy of the controller, a new algorithm was devised that accounts for the varying conductivity due to changing water temperatures. The basic idea of the new algorithm is to dynamically adjust the slope of the XY-curves that were initially determined during commissioning of the boiler.
4.3 Resistivity in Water

The electrodes are terminated in a WYE configuration, with an isolated neutral point. Given this configuration, the actual resistance of the water at full load can be determined. For the calculations, we use a 10 MW boiler running on a 10.5 kV voltage.

\[ R = \frac{V^2}{P} \]

\[ = \frac{10,500^2}{10,000,000} \]

\[ = 11.025 \Omega \]

Given the resistance computed above, the ratio between the length and area of the conducting water body at the lowest operating temperature and corresponding conductivity can be determined:
\[
\frac{L}{A} = \sigma R \\
= 11.025 \cdot 135 \cdot 10^{-6} \\
\approx \frac{1}{700}
\]

For a given water level, but at a higher operating temperature (110 °C), the actual resistance and power are calculated to be:

\[
R = \frac{L}{A} \cdot \frac{1}{\sigma} \\
= \frac{1}{700} \cdot \frac{1}{155 \cdot 10^{-6}} \\
= 9.247 \Omega
\]

\[
P = \frac{V^2}{R} \\
= \frac{10,500^2}{9.247} \\
= 11.92 \text{ MW}
\]

Therefore, with an operating temperature changing from 90 °C to 110 °C, a 22% increase, the maximum absorbed power is increased by 1.92 MW, which is a 19.2% increase in power. In practice this means that during commissioning, the initial XY-curves must be determined based on a constant temperature. Ideally, this temperature should remain constant at the lowest allowable operating temperature. This allows the algorithm to
ensure that the boiler can achieve full generating capacity at all operating temperatures.

Full load has to be achieved at the lowest allowable operating temperature. Figure 17 illustrates the increase in power when water temperature is accounted for. The curves for the two extreme operating temperatures are shown.

![Figure 17 Power Curves at Temperature Extremes](image)

The fact that the increase in power with an increasing temperature is linear allows us to derive an automatic compensation that will alter the actual level set-point from the initial set curves. This compensation has to be able to protect the boiler from overshooting its set-point, protecting the system from unwanted shut downs and improving overall accuracy of the control system.

4.4 Thermal Expansion of Water

The boiler water level is measured by a differential pressure measurement and is represented as a percentage. This percentage is proportional to the length of the level
gauge, which is mandatory on any boiler. A differential pressure transmitter simultaneously measures the pressure at the bottom and the top limits of the allowable water level. The top measurement is the reference and is equal to the boiler pressure plus the pressure of the maximal allowable water column. The bottom measurement is equal to the boiler pressure and the current water column. The actual level can therefore be calculated by subtracting the pressure of the actual water column from the pressure of the maximum allowable water column. During commissioning the differential pressure transmitter is calibrated using visual confirmation. The output of the transmitter is set at 0% with a water level barely showing in the bottom of the level gauge. The output is adjusted to 100% at a water level near the top of the gauge.

A problem identified using this principle is the thermal expansion of water. Calibration of the differential pressure transmitters is generally performed with cold water, at room temperature. The change in density of water from 20 °C to the operational temperature of 110 °C is [25]:

\[
\frac{998.3}{m^3} - 951 \frac{kg}{m^3} = 47.3 \frac{kg}{m^3}
\]

A given level at 20°C, indicated to be 100% by the differential pressure transmitter, will be physically approximately 4.7% higher at 110°C while still indicating 100%. To improve accuracy during operation it is important that the transmitters are recalibrated at operational temperature.
The change in density in the working temperature range from 90°C to 110°C is 1.6%. To guarantee correct operation in the entire working temperature range, this percentage should be taken into account in the proposed algorithm.

### 4.5 Program Improvements

The software program improvements are applied to the first three curves previously mentioned. These curves are the maximum level set-point curve, the maximum level controller-output curve and the pre-set curve for primary load-frequency control.

![Diagram](image)

**Figure 18** Control Flow PLC Program
The most significant improvement consists of temperature compensation in the curve function block. By calculating the deviation in conductivity, caused by the change in temperature, and input this deviation as a percentage in the function block, the output will be automatically adjusted. This adjustment is also dynamically made visible in the Human Machine Interface (HMI) screen by adding an extra line to the XY-chart as shown in Figure 19. The red line depicts the original curve set at the lowest operational temperature. The blue line is the result of the original curve recalculated using the new algorithm and the current boiler temperature. The green line shows the current maximum upper water level set-point with the external power controller set-point. The improved curve function block is used for the first of the curves that limits the maximum upper water level set-point. The set-point coming from the power and temperature controllers is now effectively limited according to the load demand signal coming from the load-frequency control system. This limitation is now dynamically adjusted by the algorithm as a function of the actual boiler temperature.

![Figure 19 Improved XY-Curve Visualization](image-url)
The second improvement is a simple control flow adjustment in the program. Instead of using the load demand signal to limit the output of the level controller, the actual level set-point limitation is used. This improves the accuracy of the system by effectively adjusting the maximum output of the level controller not only by the load demand, but also the maximum level set-point, which is now temperature compensated. In Figure 20 the improved XY-curve, the horizontal axis depicts the current maximum upper water level set-point.

![Graph](image)

**Figure 20** Controller Output Limiting as a Function of Set-Point

The third and final improvement is in the curve that presets the upper water level controller output with large changes in load demand, when the boiler is implemented for primary load-frequency control. In the new version, this curve is also temperature compensated making the preset position more accurate. This curve is identical to the one depicted in Figure 19.
Chapter 5: Results and Discussion

Validation of the improved algorithm was performed in cooperation with AS Scan and Hvide Sande Fjernvarme A.m.b.A. The installation is shown in Figure 21. The PARAT IEH in Hvide Sande was the first of a series of electrode boilers deployed in Denmark. The boiler has been in continuous operation since 2010. The boiler is rated at 10 MW but is only approved for operation up to 6 MW due to problems in the electrical supply grid. During initial commissioning, the low load limit was fixed at 400 kW.

Figure 21 PARAT IEH in Hvide Sande Denmark

In 2013 AS Scan proposed a change to the shape of the center rod in the electrodes. The proposed change was to elongate the spherical tip of the center rod to a cone shape. The
elongated shape resulted in a smaller contact area with the water during low loads allowing for even lower loads. The new electrode shape was successfully implemented in various electrode boilers in Denmark and was recently installed in the PARAT IEH in Hvide Sande. Another mechanical improvement to decrease low loads was an added insulating layer of TEFLON® in the bottom of the inner container. This layer was added to increase the resistance between the electrodes, resulting in the ability to operate at lower loads.

The PLC control system is remotely accessible for troubleshooting and monitoring purposes. During the commissioning, after the mechanical improvements were implemented, the derived algorithms for the control system were remotely installed and tested with local assistance from AS Scan. After the algorithms were successfully installed and verified, the boiler was engaged and for several hours the boiler was cycled through a variety of loads to ensure correct operation in the entire working range between 100 kW to 6 MW. The HMI screen, as shown in Figure 22, shows the trending of the process values and set-points of the power controller. The red line depicts the actual electrical load consumed by the boiler, measured in the main circuit breaker. The green line is the set-point that is remotely set by the load-frequency control system and the final blue line is the output of the power controller that is used as the upper water level set-point. The first test was performed with the mechanical changes in place, but without activating the new algorithms. This provides the necessary data to set the XY-curves for the lower operating temperature range.
It can be seen in Figure 22 that the changes in temperature cause some volatile responses in the controller. To ensure all important process values were registered, an Object Linking and Embedded for Process Control (OPC) data logger was used to log several key parameters. A cycle time of 500 ms was used to log the data. An excerpt of the data log is shown in appendix D. Not all recorded parameters are included in appendix D to save space. The key parameters that were logged during testing were:
With all possible responses tested, the programmatic changes were activated. Using the obtained values of the data log the new XY-curves were set. As can be seen in Figure 23, the changes to the maximum level set-point versus load demand curve and the maximum controller output versus maximum level set-point curve were set. To the left are the settings for both curves and to the right are the settings for the temperature deviation as determined from the calculations made in the previous sections and the actual temperature data from the log. The settings are accessible by the operator, but a password is needed to make any changes to the curves. This is to ensure the operator is aware of the possible severity of changes and prohibits non-authorized personnel from making changes.
Figure 23 Maximum SP / Output Curves

Figure 24 shows a graph of the error between the actual absorbed power and the external load demand signal. The first half of the graph depicts operation without the improved XY-curves in active mode. The second half shows initial operation with the new algorithm dynamically adjusting the XY-curves. It can clearly be seen that there is a significant improvement in the accuracy of the controller.
To ensure proper operation of the temperature correction, some additional changes were implemented to the controller that controls the return temperature of the boiler. This was done by increasing and decreasing the amount of hot water that is pumped through the heat exchanger. By increasing the amount of water circulated through the heat-exchanger, consequently decreasing the amount of water that is bypassing the heat exchanger, the amount of energy that is delivered to the consumer distribution grid becomes much higher and the temperature out of the heat exchanger falls. The speed of this controller was increased, to ensure a more stable return temperature to the boiler.

The improvements in boiler accuracy will have no direct economic consequences, but over time can have significant indirect implications. Less volatility and improved
accuracy of controllers will result in reduced mechanical wear of components. A reduced mechanical wear will delay replacements and periodic maintenance. To perform maintenance, the electrode boiler will have to be out of operation for multiple days to allow the boiler to cool down. Down-time results in a loss of income in addition to the cost of the maintenance and the cost for alternative sources of heat.

Improved accuracy and a more steady operation of the PARAT IEH will make it a more desirable product for prospective buyers, resulting in a larger turnover of the product.

Steady operation will result in a better load-frequency control of the electric grid, causing an overall improvement of power quality.
Chapter 6: Conclusions and Recommendations

This thesis successfully demonstrates a novel solution to improve accuracy of load-frequency control when high-voltage electrode boilers are used for this purpose. Current installations experience issues with the volatility and speed of the boiler power controller. This is partly due to the fact that the change in boiler water conductivity with temperature is not accounted for. For a typical hot-water boiler, the change in conductivity is almost 20%, which translates to a 15% increase in power consumption in the operational temperature range of the boiler. Normal boiler control is effected by a cascaded series of control-loops. The loop behavior is determined by a set of XY-curves that are determined during the initial commissioning of a boiler installation.

A new algorithm was developed that dynamically modifies the slope of certain XY-curves to account for changes in conductivity with changes of temperature. The algorithm was implemented and tested in an active installation situated in Hvide Sande, Denmark. Test results indicated that the mean power error, the difference between actual power and power set-point, was reduced to near 0% after implementing the algorithm. This provides a more accurate control when using a high-voltage electrode boiler for primary load-frequency control. The increasing number, and electrical capacity, of wind turbines, combined with the reduction of traditional power production facilities, causes greater volatility in electrical grid frequencies. This calls for a new and novel way of countering frequency deviations. High-voltage electrode boilers are a simple and inexpensive solution to this problem. The new control system, with improved accuracy
enhances the desirability the high-voltage electrode boiler for implementation in load-frequency control.

The advantages of implementing a high-voltage electrode boiler in the utility grid are numerous and depend on the application. Regardless of the application, thanks to the relatively simple construction of the high-voltage electrode boiler, in the form of a PARAT IEH, it is possible to keep the physical size and the investment cost down. The simplicity makes it possible for the customer to perform basic maintenance without the need of external experts. It also offers a great back-up source of thermal energy if problems arise with the natural gas supply. No available gas means that neither combined heat and power (CHP) engines nor gas-fired boilers can be operated to ensure a steady source of heat. Feed-back from existing users, and information supplied at time of inquiry suggest a wide area of implementation. The first series of electrode boilers, installed in Denmark by PARAT Halvorsen AS, were implemented for primary load-frequency control of the local electrical grid. There are several advantages to implementing an electrode boiler for primary load-frequency control in comparison to using CHP engines, which is the commonly used method for this purpose. Most importantly, the guaranteed area of control, which is 2% to 100% of rated power, with the control speeds associated with this area (< 30 seconds), offer a major advantage. CHP engines have greatest efficiency at 75% to 90% of the rated load with similar control speeds; the lowest recommended load is about 20%. Secondary load-frequency control does not rely on the fast control speeds, but does take advantage of the large area of control.
Another potential area of use is to convert excess wind-generated electrical energy to thermal energy. The major problem associated with wind-generated power is the uncertainty in availability of wind. This can be partially countered by lowering the generating capacity of the wind-turbines such that the availability of this capacity can be guaranteed for extended periods. The lowering of the generating capacity consequently means that potential wind-power that could be converted to electrical energy is not fully utilized. If all available wind were to be converted to electrical energy, a fast acting electrode boiler could be utilized to convert excess energy to thermal energy when available. Industrial processes could easily use this thermal energy.

A recommended future research opportunity is to perform a feasibility study for the implementation of high-voltage electrode boilers for load-frequency control in the United States. The main issue will be to find a suitable thermal energy consumer. Several larger cities like New York and San Francisco have extended district heating and a non-polluting source of heat as a by-product from load-frequency control might be very attractive. With the ever-increasing foot-print of bigger cities, the necessity of decentralized generation becomes a feasible opportunity. Problems with load-frequency control that may arise from decentralized generation, may be mitigated by implementing high-voltage electrode boilers.

An additional topic that has immersive research opportunities is thermoelectric generation; for example, using high-voltage electrode boilers to generate thermal energy from excess electrical energy, generated by wind-turbines. This thermal energy can easily be stored and used when needed.
be stored in massive accumulation tanks in the form of water or other materials that have good thermal properties, like molten salt. The problem that is encountered is the temperature range. A typical PARAT IEH high-voltage electrode boiler can produce water of about 230 °C, at a pressure of 30 bar, but additional overheating of the steam is necessary to make it suitable for electricity generation by steam turbines.

The successful implementation of the algorithm presented in this thesis provides a fundamental building block toward expanded use of high-voltage electrode boilers for load-frequency control with the added benefit of thermal energy as a by-product for use by various consumers. The enhanced control algorithm is particularly relevant in applications with increased volatility due to electrical power production by wind-turbines.
References


Appendix A: PARAT IEH Typical Arrangement
Appendix B: PARAT IEH Product Sheet

High Voltage Electrode Boiler
Steam and Hot water
From renewable POWER to HEAT with PARAT electrode boiler

From minimum to full load in under 30 seconds.

PARAT; boilers since 1920
Our electrode boiler has been designed and developed by our in-house engineers and manufactured in our workshop in Norway for more than 20 years.

Our boiler history goes all the way back to 1920. Since we started we have delivered more than 7000 boilers to the Norwegian market alone. Today we are the largest supplier of boiler systems in Norway.

Electrical grid regulation
Increasing power generation from wind and solar systems have created a demand for fast frequency regulation of the electrical power grids. The PARAT electrode boiler can be used for primary regulation with less then 30 seconds response time from minimum to full load.

Converting electrical power to heat makes it possible to accumulate renewable energy in periods of overproduction. Our partner A/S SCAN in Denmark has installed more than 7 PARAT electrode boilers in the Danish grid.

Steam and hot water
The electrode boiler is delivered both in a steam and hot water version with maximum pressure of 30 barg.

- From cold to full load in less than 15 minutes
- 30 seconds from minimum to full load
- Minimum load is below 2%
- No earth current
- Compact design - up to 50MW in one unit
- No low voltage transformer required
- No Electrode wear
- Minimum maintenance required
**Area of use:**
- Steam and Hot water production when electricity is cheap
- Grid regulation
- Backup boiler with fast startup time
- Load balancing in gas turbine systems
- Extremely compact for large power loads

**Design codes**
We deliver the boiler CE marked according to PED/97/23/EC with boiler code EN12953 or ASME stamp. The IEH is also available in EX version for installation in zone 2 hazardous areas.

**Marine version available**
PARAT has developed a patented system for marine installation and application. The PARAT electrode boiler is in full operation on the deck of the FPSO BW Pioneer in the US Gulf of Mexico.

**Control system**
We have used our experience to develop a modern and robust boiler control system which is easy to use. The boiler is also available with PARAT remote monitoring system. This enables web-based remote monitoring of the boiler plant from anywhere in the world. This also includes online troubleshooting and upgrades of the control software from the PARAT Halvorsen AS service centre in Norway.

---

### Technical data

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Boiler outer dimensions including insulation mantle. Design pressure 16 barg. We reserve the right to make changes.

---

PARAT IEH: High Voltage Electrode Boiler

---

**www.parat.no**
**Appendix C: Program Code**

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Author: Version: 0.1
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**Block: FB44**

**Network: 1**

Determine deviation factor and construct setpoint line, actual factor is being set from outside function block.

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    1.000000e+002   
/R
T  #Dev_Factor   //convert in factor    #Dev_Factor
   
L  #Y0    //calculate new Y values     #Y0
T  #Y0_dev
   
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T  #Y1_dev
   
L  #Y2    #Dev_Factor                     #Y2
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```
L #Y9  #Dev_Factor
T #Y9_dev  #Dev_Factor
L #Y9  #Dev_Factor
T #Y9_dev

Network: 2

A #Curve_On  //if curve is inactive, jump to last statement
JNB END //compare lowest value to controller
L #X0  #Controller
JCN #X0  //if controller is higher than X0 jump to next part
L #Setpoint //if lower, move lowest Y to output
T #Setpoint //jump to last statement
JXO: L #X1  //if controller is higher than X1 jump to next part
T #Controller
JCN #X1  //if lower, calculate difference between X1 and X0
L #X1  #X0
R #DiffX  //calculate difference between Y1 and Y0
L #Y1_dev  #Y0_dev
R #DiffY  //calculate difference Y per X
L #DiffX
R #YbYX  //calculate where on X line controller is
L #Controller
T #Output //calculate Y belongs to this position
L #Output
T #Setpoint //jump to last statement
JX1: L #X2  //as previous...
T #Controller
JCN #X2  //if controller is higher than X2 jump to next part
L #X2  #X1
R #DiffX  //calculate difference between Y2 and Y1
L #Y2_dev  #Y1_dev
R #DiffY  //calculate difference Y per X
L #DiffX
R #YbYX  //calculate where on X line controller is
L #Controller
T #Output //jump to last statement
L #Output
T #Setpoint //jump to last statement
JU END //if controller is higher than X1 jump to next part
T #Controller
Appendix D: Excerpt from Process Data

SIMATIC 000070 Test PLC/SIMATIC 300(1)\CPU 314C-2 PN/DP\...\FB44 - <offline>

03/17/2014 02:57:29 PM

SIMATIC T FL RT FL/R FL JI.K FL/R FL •R TL JU LX8 LX9
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L $X8 #Controller $X8
$YbX $YbX #YbX
#Output $YbX $Output
#Setpoint $YbX $Setpoint
JU END

JX9: L $X9 #Controller $X9
L $X8 #Controller $X8
#YbX $YbX #YbX
#Output $YbX $Output
#Setpoint $YbX $Setpoint
JU END

END: L #Controller #Controller
L #Y9 dev #Controller
#Setpoint #Y9 dev $Setpoint

03/17/2014 02:57:29 PM

Page 6 of 6
### Appendix D: Excerpt from Process Data

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- **Load Dem. PV [kW]**: The desired load demand in kilowatts for the process.
- **Power PV [kW]**: The actual power output in kilowatts for the process.
- **Power SP [kW]**: The setpoint or target power output in kilowatts for the process.
- **Power LMM [%]**: The percentage deviation from the load demand.
- **Temp. PV [°C]**: The temperature of the process.
- **LVL Upper PV [%]**: The upper limit percentage deviation from the load demand.
- **LVL Upper SP [%]**: The upper limit percentage deviation from the setpoint.
- **Max Output [%]**: The maximum output percentage deviation from the load demand.
- **Max SP [%]**: The maximum setpoint percentage deviation from the load demand.
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