

UNIVERSITY OF THE WITWATERSRAND

Aspects of Autonomous Demand Response through Frequency Based Control of Domestic Water Heaters

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*A dissertation submitted in fulfilment of the requirements
for the degree of Master of Science in Engineering*

in the

School of Electrical and Information Engineering

July 2017

Declaration of Authorship

I, DOUGLAS COOPER, declare that this dissertation titled, “Aspects of Autonomous Demand Response through Frequency Based Control of Domestic Water Heaters” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this dissertation has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this dissertation is entirely my own work.
- I have acknowledged all main sources of help.
- Where the dissertation is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Abstract

Engineering and the Built Environment
School of Electrical and Information Engineering

Master of Science in Engineering

Aspects of Autonomous Demand Response through Frequency Based Control of Domestic Water Heaters

by DOUGLAS COOPER

This dissertation presents the design and testing of controllers intended to provide autonomous demand response, through the use of water heater loads and grid frequency measurements. The controllers use measured frequency as an indication of the strain on a utility grid, which allows demand side management to be isolated from any form of central control. Water heaters can operate as flexible loads because their power consumption can be dispatched or deferred without directly impacting users. These properties make it possible to control individual water heaters based on the functioning of the grid, rather than end user input. The purpose of this research is to ultimately provide a low-cost alternative to a traditional Smart Grid, that will improve the resilience of a grid without negatively impacting users. The controllers presented here focus on ensuring that users receive hot water, while attempting to reduce any imbalance between power generated and power consumed on the grid. Simulations of these controllers in various situations highlight that while the controllers developed respond suitably to variations in the grid frequency and adequately ensure end users receive hot water, the practical benefit of the controllers depends largely on the intrinsic characteristics of the grid.

Acknowledgements

The work done for this dissertation would not have been possible without assistance, and hence I would like to thank the following people. Firstly to my family and Kate, who supported and encouraged me throughout my postgraduate years. To all of the staff in Genmin Lab, thank you for helping set up and experiment on the geysers. To the members of the FEET forum for posing questions and solutions, especially Jessie for driving the water heater tests and sharing her data. Finally to Prof Cronje for the constant supervision, advice and thought provoking discussion.

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Abbreviations

AC	A lternating C urrent
DC	D irect C urrent
RTD	R esistance T emperature D etector
PLC	P rogrammable L ogic C ontroller
CSV	C omma S eparated V alues
SAGC	S outh A frican G rid C ode
HVAC	H eating V entilation and A ir C onditioning

Chapter 1

Introduction

There are two main aspects of modern AC electrical grids that have led to the research presented here. The first has to do with the installation of Smart Grids in developing countries and the second is the goal of providing flexible demand response on any grid.

The research here is directed towards developing a form of autonomous demand response at a lower cost than a conventional Smart Grid. This demand response will improve the resilience of the grid by reducing the load during times of strain, while attempting to limit the impact any automatically controlled load has on users.

1.1 A Guide to this Dissertation

The structure of the document is as follows: First the background, introducing important aspects of the research, is presented in Chapter 2. A literature review showcases work related to this research in Chapter 3. Chapter 4 discusses the functioning of an AC grid and presents a basic analysis of the South Africa grid frequency. Chapter 5 discusses using water heaters as an energy store, to provide load levelling, and presents a mathematical model for water heater standing losses.

Chapters 6, 7 and 8 present forms of control designed to provide autonomous demand response; the general structure of the simulations performed; and the results of specific simulations. A summary of the key findings from the simulations and experimentation is presented, along with recommendations for further research, in Chapter 9. Finally, Chapter 10 concludes and summarises the work done. Figure 1.1 below gives a further schematic of the research presented here.

Appendices at the end of the document provide further details of supporting work. These include detailing the physical test bed for a water heater; a contextual comparison between heating and cooling appliances; and excerpts of simulation code.

1.2 Research Question

The research question to be answered, in its most basic form, is as follows: “Is it viable to control individual electric water heaters, based on a measurement of the grid frequency and the water temperature, in order to reduce strain on the grid while ensuring users receive suitably heated water?”

In a broader and “real world” sense, the research presented here is done in an attempt to develop low cost autonomous load controllers, that can provide demand side management.

1.3 Research Goals

Beyond answering the research question, the following goals for the research will need to be achieved.

Firstly: an accurate and generic mathematical model of electric water heaters needs to be developed. This model is intended to be simplistic while still capturing the notable aspects of water heater operation.

Secondly: the theoretical development of generic controllers for water heaters that will ensure users receive hot water and that the changing grid load requirements are consistently met.

Thirdly: An expandable model of a utility grid needs to be developed. It must contain the water heater and controller models mentioned above and incorporates the impact their operation has on the grid frequency. This grid model will be simulated and used for analysis into the effectiveness and limitations of the controllers in specific situations.

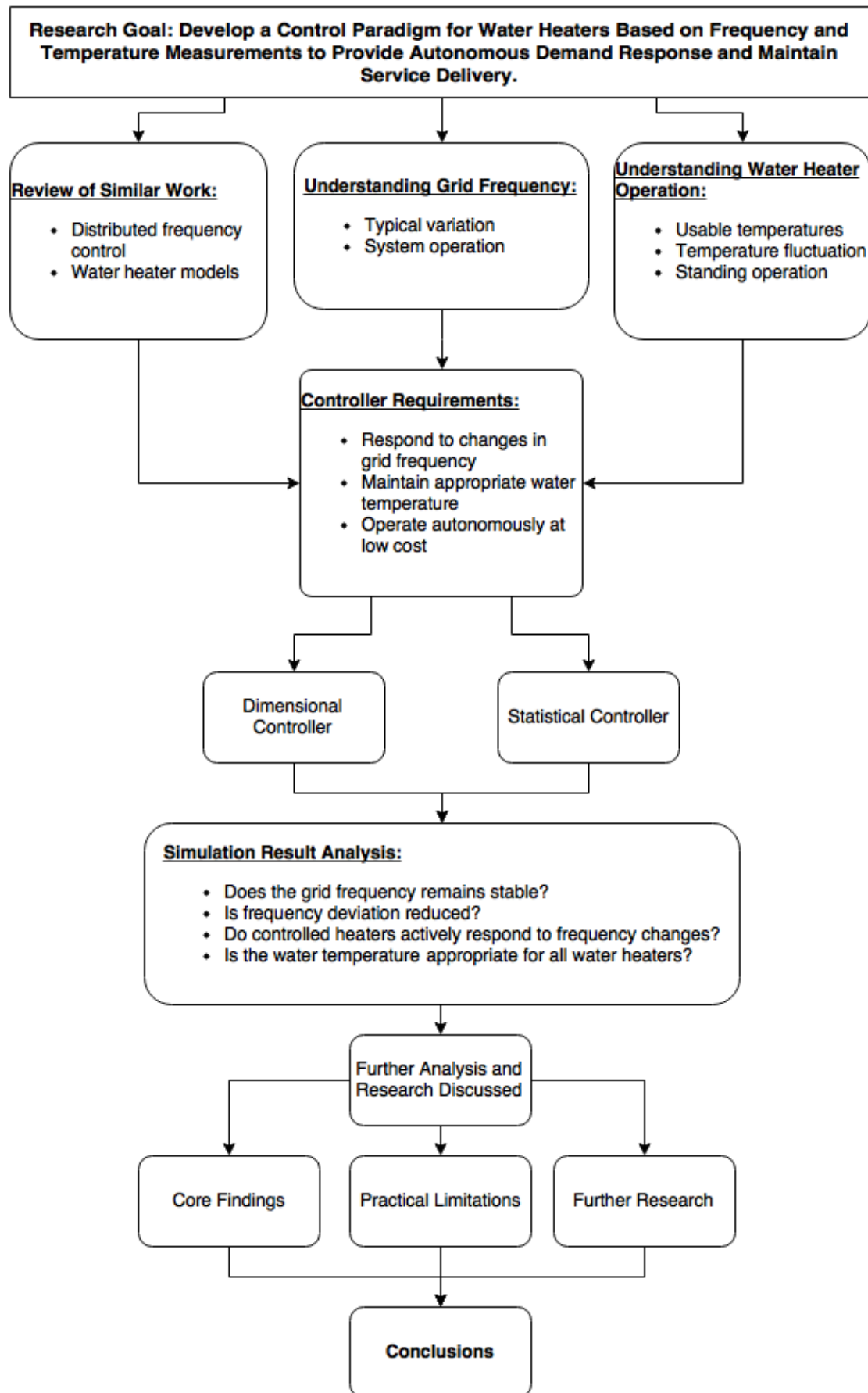


FIGURE 1.1: Flow chart overview for the dissertation presented

Chapter 2

Background

To understand the reasoning behind this research a broad, high-level background is discussed below. The desire to improve the operation of a traditional national grid has led to Smart Grids, which allow for direct and intelligent control of both loads and power sources. A Smart Grid facilitates demand response, making power flow in a utility grid more flexible and robust.

This Chapter presents a potential problem with conventional Smart Grids and discusses how leveraging the relationship between grid frequency and power imbalance could provide a means to low-cost autonomous demand response. Finally the idea of a flexible load is presented, which would aid in reducing the impact that demand response has on end users.

2.1 Improving Energy Efficiency

Throughout the world, there is a movement towards more efficient energy usage. Among other things, this has resulted in more efficient appliances, an increase of renewable energy generation and the introduction of the Smart Grid.

2.1.1 Smart Grids and the Inherent Problem

The term Smart Grid typically refers to the use of a communication network with controllers to improve power delivery and power utilisation, through intelligent monitoring and control of the loads and power sources on the grid. While the implementation of a Smart Grid is by no means trivial, it can be done essentially with “brute force”: sensors need to be fitted throughout the system; a controller capable of reading from the sensors

and performing optimising control is required; and a communications network dedicated to the control must be installed. The necessity for such a complex solution leads to a fundamental problem with Smart Grids: the infrastructure and cost required to install Smart Grids renders them unfeasible in third world or developing countries.

2.1.2 Demand Response

One of the most basic functions of a Smart Grid is to facilitate demand response. That is, loads on the grid can be actively controlled, such that any imbalances between power generated and power consumed can be mitigated to reduce strain on the grid. Furthermore, this demand response allows for intelligent load shedding that minimises the impact on end users when the electricity demand cannot be met. Especially in countries where load shedding is a common occurrence (mostly developing countries) this distributed control of loads can be used to turn off appliances that are not essential, rather than the typical case where entire suburbs are completely disconnected from the utility grid. Unfortunately, as mentioned above, it is not generally viable to install a Smart Grid to provide demand response in the countries that would benefit the most.

2.2 Relating Grid Strain to Frequency

In any electrical power distribution system, there needs to be a balance between the supplied power and the consumed power. On a small scale, it is a simple matter to design the system to exactly meet requirements. However, on a larger, expanding system that supplies numerous user-driven loads it becomes difficult to account for all the variation in consumption. On a utility AC grid this power imbalance is relatable to the grid frequency, and thus the grid operators use the frequency as an indication of the strain on the grid. If the frequency goes above the nominal value, generators are slowed down or disconnected to reduce the power supplied to the grid. Conversely, if the frequency goes below the nominal value, generators are sped up to increase the power supplied, or loads are disconnected to decrease power consumed. This concept, relating grid strain and frequency, is discussed more thoroughly in Chapter [4](#).

2.3 An Autonomous Grid

To achieve the goal of improving energy efficiency at a low cost, the relationship between the grid frequency and power balance can be exploited to mimic aspects of a Smart Grid. It is possible to infer the state of the grid using a frequency measurement. This

measurement can then theoretically be used in controllers for individual loads to provide autonomous demand response. This solution would remove the need for the central controller and communications network that form a large portion of the cost of a Smart Grid.

Figure 2.1 below presents a basic overview of a national grid. From primary generation, electricity is distributed geographically throughout the country; at a suburban level power is connected to individual houses, where it is further spread to separate appliances. A traditional grid has control over power generation and basic on-off control of the supply at a suburban level. Conventional Smart Grids allow for advanced control over nearly all aspects of the grid: from generation and transmission, down to micro-managing the usage of individual households. The scheme proposed in this dissertation, for autonomous demand response, utilises controllers installed in households on a traditional grid that independently provide control of domestic appliances. The autonomous control can measure aspects of the grid at a local, household level.

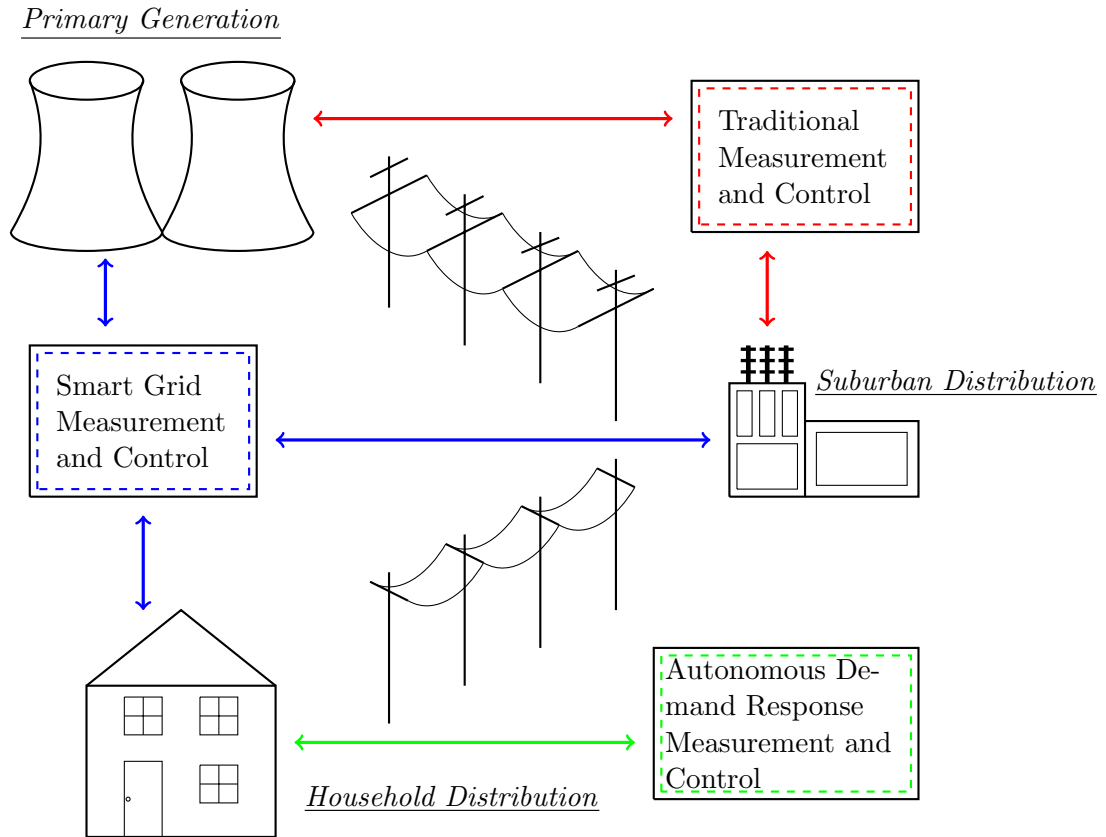


FIGURE 2.1: Overview of the measurement and control for various grid infrastructures.

2.4 The Flexible Load

The core limitation of the theoretical autonomous demand response is a lack of precision: loads turning off or on automatically at uncontrolled times are likely to negatively impact end users. To counteract this it is proposed that “flexible” loads be controlled. These loads are defined as being both dispatchable and deferrable. Dispatchable in the sense that these loads can consume power usefully without affecting users, and deferrable in the sense that users receive service from the load even if it is not currently consuming power. Thermal appliances provide good deferrability at a domestic level due to thermal inertia, and heating appliances in particular provide good dispatchability because they are large, resistive loads. A further analysis into thermal loads is presented in Chapter 5. In the rest of this document loads with the combined characteristics of dispatchability and deferrability will be referred to as flexible.

2.5 Conclusion

This Chapter has presented some basic ideas and reasoning behind the research. These include providing autonomous demand response as an alternative to a traditional Smart Grid. Autonomous demand response can be achieved through grid frequency measurements, and through utilising flexible loads, which would improve grid stability without inconveniencing users.

Chapter 3

Literature Review

This Chapter contains discussions on work previously done, that links to or forms the basis for aspects of the research presented in the rest of the dissertation. This includes using domestic appliances as a means to control grid frequency and to reduce the load in times of grid strain. The modelling of water heaters is also an element of the research and various models that have been developed are presented below.

3.1 Smart Grids

As mentioned, a conventional Smart Grid leverages a large number of sensors, meters and powerful controllers to allow for refined control over the majority of a grid. The majority of the literature below focuses within a Smart Grid capable environment.

3.1.1 Autonomous Demand Response

One of the core elements of this research is attempting to facilitate autonomous demand response: the ability to alter the load on a grid automatically without the need for powerful controllers. Standard demand response (as on a Smart Grid) can be understood as a form of control with very fine precision when controlling loads on the grid. Rather than the basic grid control over suburb-sized areas, demand response aims to allow system operators direct control at a household level. It can also be implemented so that users can control their consumption more directly. These aspects of demand response mean that the load on the grid can be levelled to reduce peak consumption, and (with input from the users) the impact on user lifestyle is minimal. [1]

Work has been done in simulating autonomous demand response in various ways. These include: proportional load controllers that attempt to regulate grid frequency; market-based distributed response with electric vehicles; and potential controls and communications for bidirectional power flow in a decentralised Smart Grid. [2] [3] [4]

3.1.2 Distributed Frequency Control

With or without the load being automatically controlled, any switching of large loads (be they individually large or an aggregation of smaller loads) will affect the grid frequency. Research has been conducted (in the following papers) into the impact that controlled loads will have on the grid, as well as on improving the stability of the grid frequency through load control.

In [5] the authors work to define metrics that aid in the analysis of the impact that autonomous load response has on the grid frequency. Their results, after multiple simulations, show the controllers they developed do provide a marginal improvement over traditional frequency regulation.

Work done in [6] looks into providing demand response in homes with Smart meters installed. It is shown that autonomous control is more feasible with purposeful delays between applying control to loads. From that, commonly used appliances are grouped such that different amounts of load can be shed for different amounts of time in the case of a supply loss. The purpose was to minimize the impact on end users by limiting the maximum amount of time any single appliance can be off for. The core limitation with this work is that there are still set amounts of time for which an appliance will not be useable.

A decentralised system is theorised in [7] that makes use of isolated controllers which run through a stochastic process to determine how to control appliances in response to the grid frequency. The paper focuses on battery charge controllers which will be able to consume excess load, as well as reduce overall consumption, and still supply other appliances. This powerful dual nature of being able to sink power as well as defer consumption is an important feature in the rest of the research presented in this dissertation and is discussed in more detail in Chapter 5.

3.2 Appliances Impacting the Grid

The Grid Friendly Appliance Project focused on the impact that automatically controlling loads has on the end user, rather than on the grid. Carried out in California, this

project installed appliance controllers in suburban households that would turn the appliances off if the grid frequency dropped. In [8] and in [9] the setup, experimentation and results of the project are discussed in detail. While the scope of the project was limited to providing a fast reduction in load consumption during a sudden loss of generation, the research shows how selection of the appliances to be controlled resulted in a minimal impact to the end users.

Further work done by the above lead researcher can be found in [10], which evaluates the effectiveness of water heaters in providing load regulation. The models developed are comprehensive and simulations find that in their scheme the controlled heaters provide notable regulation. It must be noted that the form of control design utilises a control signal to determine when load regulation must take place. Similar research can be found in [11] where the authors investigate the impact that various water heater parameters can have when using said heaters to regulate load on a grid.

3.3 Modelling Electric Water Heaters

Electrical water heaters can be modelled with varying degrees of complexity. The most simplistic model utilises basic thermodynamic equations while more complex models can be found in the literature below.

The work done in [12] uses a basic thermostatic model to analyse how a more intelligent system could potentially create a usage profile to provide autonomous load limiting. The proposed system is limited by how well it can learn the usage patterns and will not be able to react dynamically to sudden strain on the grid. Regardless of the limitations, the adaptive nature of the system could be used to ensure better service delivery based on the household usage.

A far more accurate model is found in [13], where the thermal stratification of water heaters is taken into account, along with the impact that water draw-off has. This model divides the water in the tank into layers with individual temperatures that interact through thermal conduction. Comparisons between the simulated model and measured data (after model parameters have been estimated through various methods and algorithms) show a high level of accuracy.

3.4 Combined Work

Perhaps the most notable work that combines both thorough water heater modelling and intelligent load response can be found in [14]. The research presented combines a

stratified thermal model for a water heater (including water draw-offs generated probabilistically) with various control schemes for a Smart Grid environment. The simulations performed within show the direct interaction between demand response based control and the availability of hot water for individual users.

3.5 Conclusion

Discussed above is some of the previous work and research done towards the goals of providing intelligent demand response and utilising water heaters more effectively. The majority of the work demonstrates the feasibility of using water heaters (and other domestic appliances) to regulate load on a grid, and points to the usefulness of fully modelling water heating systems.

Chapter 4

An AC Electrical Grid

Throughout the world, AC utility grids operate on similar principles. Large power sources (typically coal fired or nuclear power stations) generate the electricity that is provided to the users. The grid transmission network distributes the electricity at higher and lower voltages throughout the network until users are supplied. Below are observations regarding typical grid operation, as well as a basic analysis of the grid frequency in South Africa.

4.1 Supply, Demand and Power Imbalance

As briefly discussed in the Background chapter, there is a relationship between the power imbalance on a grid and the frequency of the grid. In Kundar [15] the frequency and power relationship of an AC grid is reduced to the form seen in the Equation 4.1 below.

$$\Delta f = \frac{1}{M_s + B}(\Delta P_e - \Delta P_l) \quad (4.1)$$

Where:

- Δf is the change in average frequency
- M_s is the equivalent inertia of the system
- B is the inverse of the frequency sensitivity to input power change
- ΔP_e is the change in power generated
- ΔP_l is the change in power consumed

This equation represents a simplified first order model of the grid that approximates it as a single combined generator and a single combined load. While it is not the most accurate representation, it is suitable for this research as it allows for an approximation of the impact that a changing load will have on the grid frequency. Discussion around this model, and more sophisticated models for an AC grid, can be found in [16] where higher order models are proposed and developed.

It can be seen From Equation 4.1 that as the frequency drops, either power must be injected into the grid to restore it (traditionally done by increasing generator rotation speed), or loads must be removed. If the frequency rises then loads must be added in order to restore it, or generators must be slowed down.

As there are many fewer power stations than there are loads, and the electricity service provider has more direct control over them, any power imbalance is usually restored through control of the stations themselves. Exceptions to this are: when pumped storage is used either to dump excess energy or supply a deficit (further discussed in Chapter 5) and in extreme cases where suburbs are disconnected to drastically reduce the national load (known as load shedding).

4.2 The South African Grid

In South Africa Eskom (the national electricity provider) relies mostly on traditional coal fired power stations. Operators control the transmission and distribution of the produced electricity according to the Grid Code, parts of which are discussed below.

4.2.1 The South African Grid Code

To ensure that safety and operating requirements are met, the South African Grid Code (SAGC) prescribes and defines the standards for all aspects of the grid. While the SAGC provides details from electrical distribution and transmission to the connection of renewable sources to the grid, the aspect that is most pertinent to this research is the regulation of the grid frequency. Figure 4.1 below shows a visual representation of the bands of control for the grid frequency. This information is adapted from [17].

The SAGC can be explained as follows. While the frequency remains within the dead-band, no action is taken by the system operators. Above the deadband, primary and secondary governors are used to lower the frequency, these are essentially methods to slow the generators down. These methods include: applying physical brakes to the turbines, using the excess power to supply pumped storage, or dispatching loads to

consume the excess. At even higher frequencies, generating units start to be purposely disconnected from the grid to prevent damage from the rotational speed.

Below the deadband there is an initial governor response whereby the turbines are sped up to once again produce the nominal 50 Hz. Lower than the point where mechanical means can restore the frequency, there is voluntary and mandatory load shedding. Voluntary load shedding sees large power consumers in the country (such as mines) reduce their electricity usage either by restricting the machines used or powering their site with personal generators. Mandatory load shedding refers to the controlled disconnection of geographically defined areas from the grid. Suburbs lose power based on a predetermined roster to insure that the majority of the country receives uninterrupted electricity.

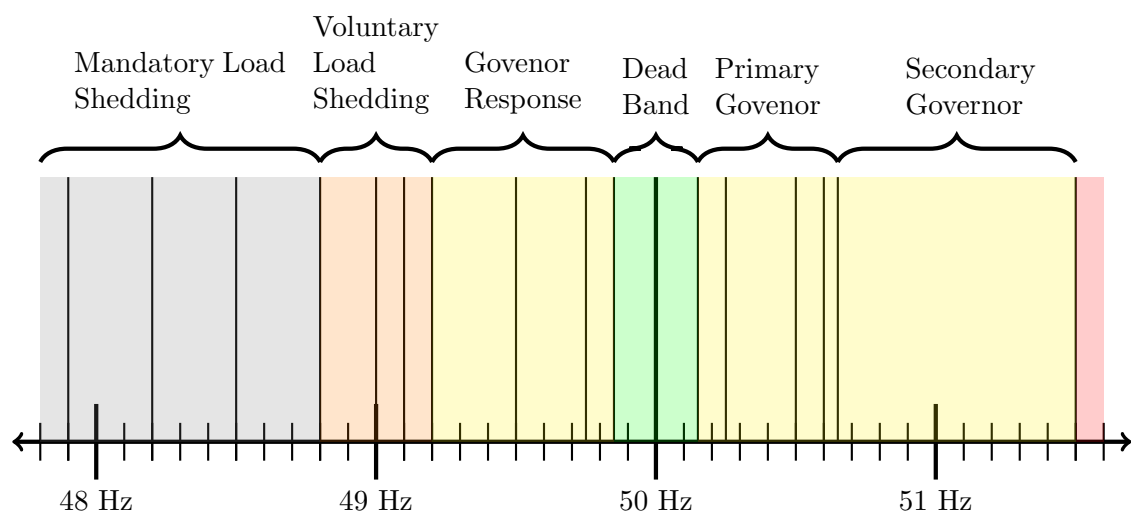


FIGURE 4.1: Frequency bands of the national grid.

4.2.2 Analysis of the South African Grid Frequency

Figure 4.2 shows a sample of the grid frequency and a histogram showing the expected frequency deviation from the nominal 50 Hz can be seen in Figure 4.3.

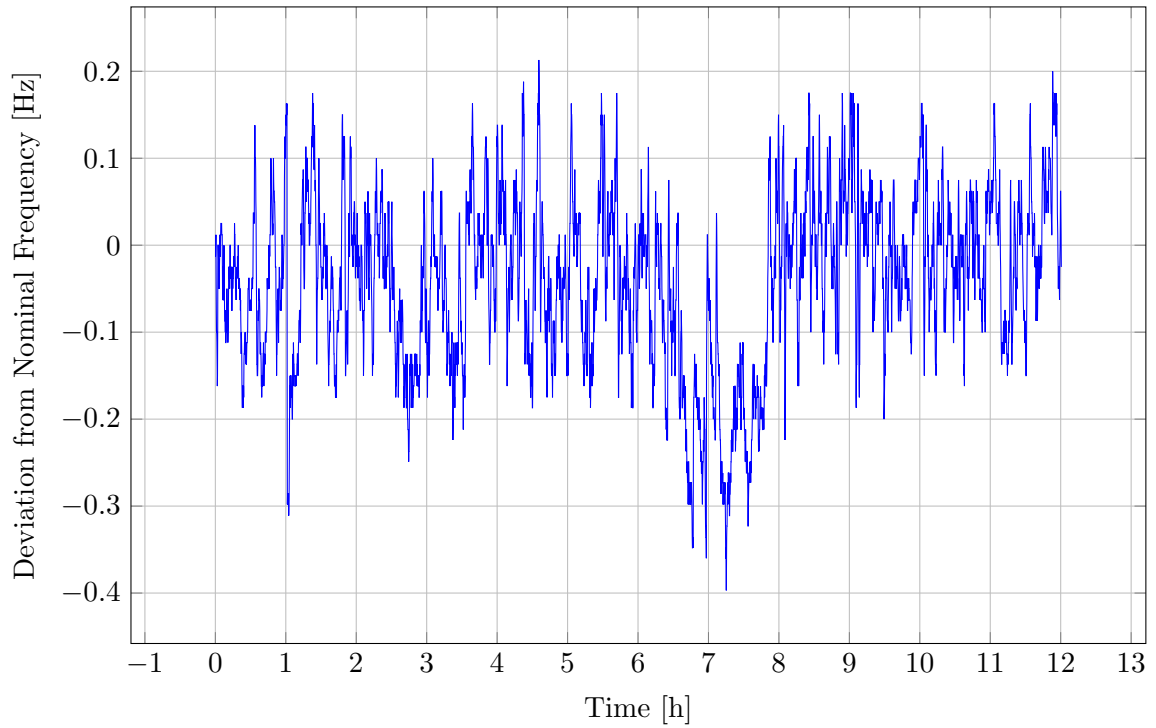


FIGURE 4.2: 12 hour sample of the South African grid frequency.

The Figure above shows how the frequency moves erratically around the nominal level throughout a 12 hour period. The effect of the system operators can be seen as the frequency rarely leaves the deadband (0.15 Hz above or below nominal) and when it does it is restored. The large dip around 7 hours can be attributed to a large national load such as a morning or evening peak.

The histogram in Figure 4.3 below provides further insight into how often the frequency reaches certain deviations from the normal. Once again it is clear how the frequency typically remains within the deadband, though the spread does reach a minimum of 49.65 Hz and a maximum of 50.23 Hz. The data to create this histogram was collected throughout April 2015.

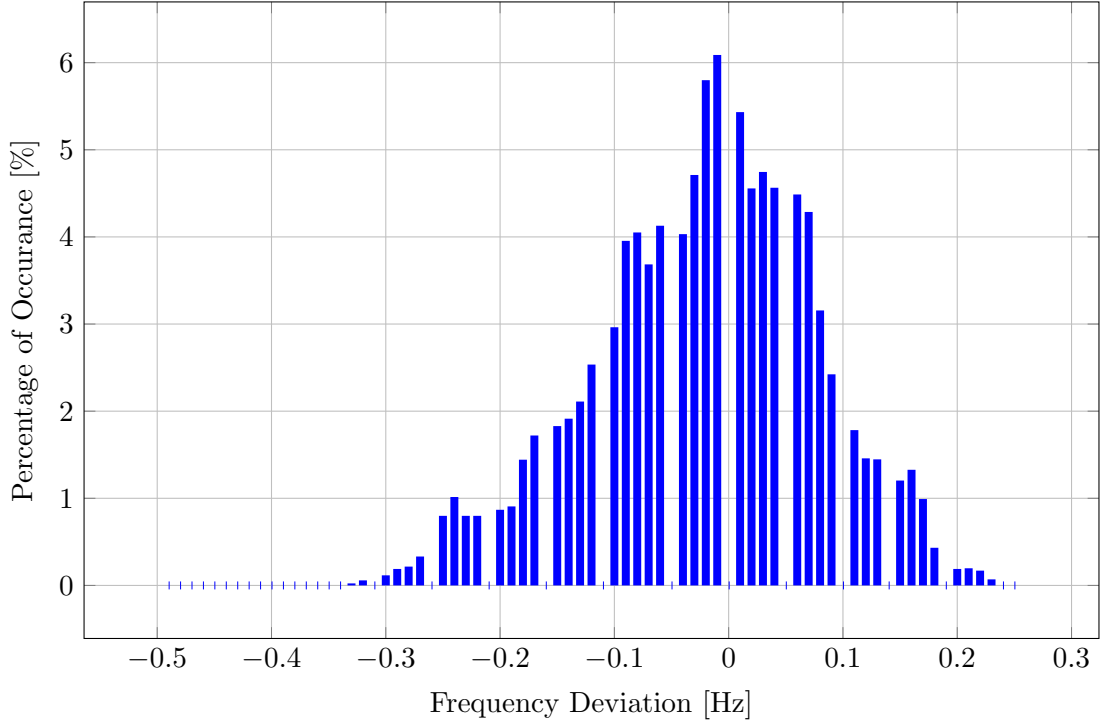


FIGURE 4.3: Distribution of grid frequency deviation from 50Hz.

4.3 Conclusion

An equation was presented that describes the basic relationship between the power balance on an AC grid and the grid frequency. The equation infers that any change of power consumption or generation on a grid will impact the frequency, based on the intrinsic characteristics of the grid. The standard operating procedures of the system operators in South Africa were summarized and simplified, showing what basic actions are taken depending on the grid frequency. A sample of the frequency was presented and analysed showcasing the typical state and trend of the grid as well as the typical frequency deviation from normal.

Chapter 5

Thermal Appliances as Passive Energy Storage

5.1 Storing Energy

At a fundamental level, storing energy allows power consumption to be delayed. With the addition of storage not all power being generated needs to be consumed and the store of energy can be used to supplement the primary generation. On a small scale, storage can be actualised with batteries as seen in off-grid solar installations for individual houses. On a national scale pumped storage schemes are utilised: energy is stored by pumping water into a reservoir and retrieved by letting that same water power hydro-electric generators later.

Thermal appliances such as water heaters, fridges and freezers provide an alternative way to store energy: while they cannot actively return electricity to the grid, they are what is referred to as deferrable loads. Deferrability means that the ability to use the appliance is not entirely dependent on whether or not they are actively consuming power.

5.1.1 Cooling and Heating Appliances

Both heating and cooling appliances operate in a similar way: they consume power while reaching a specified temperature and then (once turned off) the temperature moves to be in equilibrium with the ambient temperature through thermal radiation. Users receive standard service from the appliance throughout these cycles of fluctuating temperature. However, due to the sensitivity of operating temperatures and power consumption, the viability of these different appliances (as deferrable loads) varies.

The reasoning in Appendix B is used as the basis for considering domestic water heaters to be more suitable than domestic cooling devices for use as energy stores. The core operation feature of water heaters is that they have a higher power rating; this makes them better dispatchable loads than the lower powered cooling devices. Deferrability is harder to generically compare, as the insulation around each device will be the main determining factor as to how long it can remain off for while still maintaining a useful temperature. However: with the higher power consumption as well as the larger temperature band for water heaters, it is clear that controlling water heaters non-traditionally will have a larger impact on the grid and a smaller impact on end users.

5.2 Modelling Water Heater Operation

There are a few key parameters that must be understood in order to develop a mathematical model for a water heater. The sections below describe these parameters and the comparison between simulated models and results from live testing. It must be noted that there are two installation configurations for water heaters: vertical and horizontal. Depending on this configuration the key parameters differ and thus models for both variations must be developed. Due to its simpler nature, the vertical configuration is analyzed below, though a uniform temperature model can also be used for a horizontal configuration.

For the purpose of this research the “useable” temperature for hot water is above 50 °C. Provided that the average temperature of the water within the tank is above this it is assumed that users will be able to comfortably make use of the water.

5.2.1 Common Water Heater Parameters

Water heaters can be understood as systems with two key flow aspects. One, heat flow: temperature being added to and removed from the system. Two, water flow: water being added to or removed from the system. Figure 5.1 below details and labels these flows.

Ultimately it would be ideal to be able to determine a generic form of these two parameters. The generic form of heat flow can then be applied to any water heater by use of its specifications, namely: power consumption, volume capacity, and rated standing losses (inaccuracies arise with widely varying ambient temperatures). In the work presented later, water flow is approximated through reducing the water temperature within the tank to indicate users drawing off hot water. Realistically the generic form of water flow

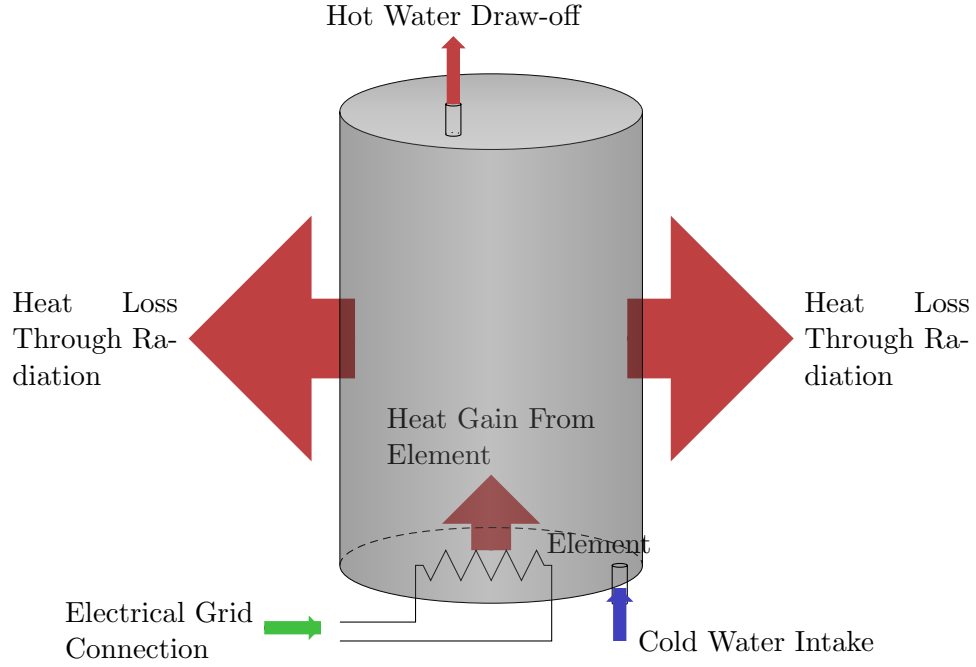


FIGURE 5.1: Heat and water flow in a water heater.

depends on individual usage patterns and to incorporate the flow accurately variable and probabilities describing the usage would need to be determined.

5.2.2 Typical Standing Operation

Without water being removed from the system, a thermostatically controlled water heater operates in a predictable manner. The element turns on and heats the water until a specific pre-set point is reached (typically around 70 °C), the element then turns off and the heat radiates into the surrounding air. With the assumption that the water temperature within the tank is uniform, then Equation 5.1 can be used to describe the heating of the water and Equation 5.2 can be used to describe the cooling. These equations are adapted from Newton's thermodynamic laws in order to show the effect of each observed time step "n".

$$T_n = T_{n-1} + \frac{P}{mc} \quad (5.1)$$

$$T_n = T_a + (T_{n-1} - T_a)(e^{-r}) \quad (5.2)$$

Where:

- T_n is the water temperature at the current time in °C
- T_{n-1} is the water temperature one second past in °C
- P is the power of the water heater element in kW
- m is the mass of the water in kg
- c is the specific heat capacity of water in J/g °C
- T_a is the ambient temperature in °C
- r is the convection coefficient

Figure 5.2 shows the results of a physical test, where the heater was allowed to reach a steady state temperature and then cool over an extended period. From this it can be seen that the water temperature remains useable for extended periods of time, provided no water is drawn off.

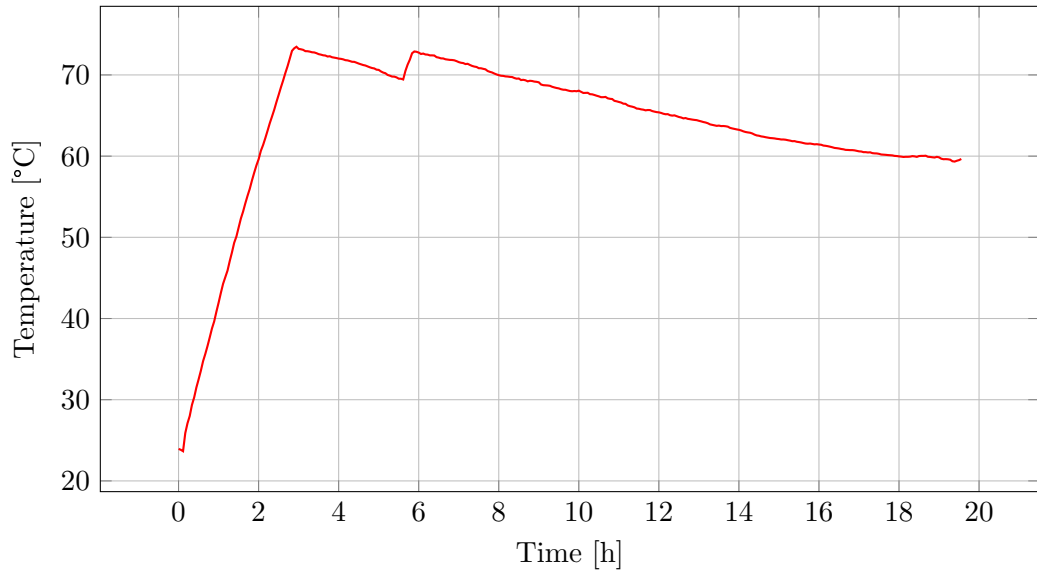


FIGURE 5.2: Sample of the temperature fluctuations in a thermostatically controlled water heater.

Next, Figure 5.3 shows the measured temperature from experiments performed in Appendix A (*i.e.* a 100l, 2kW water heater) compared to a simulation done that mimics the scenario and uses the Equations presented above. It can be seen that after a cycle of the thermostat, the simulation deviates from the measured results: this can be

attributed to the marginally random switching point of the physical thermostat. The important fact is that the simulation accurately tracks the heating and cooling trends. The convection coefficient for a particular case can be determined through iteratively comparing simulation results (where only the coefficient was changed) to the measured results until a best match is found. In the case above the coefficient was found to be 3.5×10^{-6} .

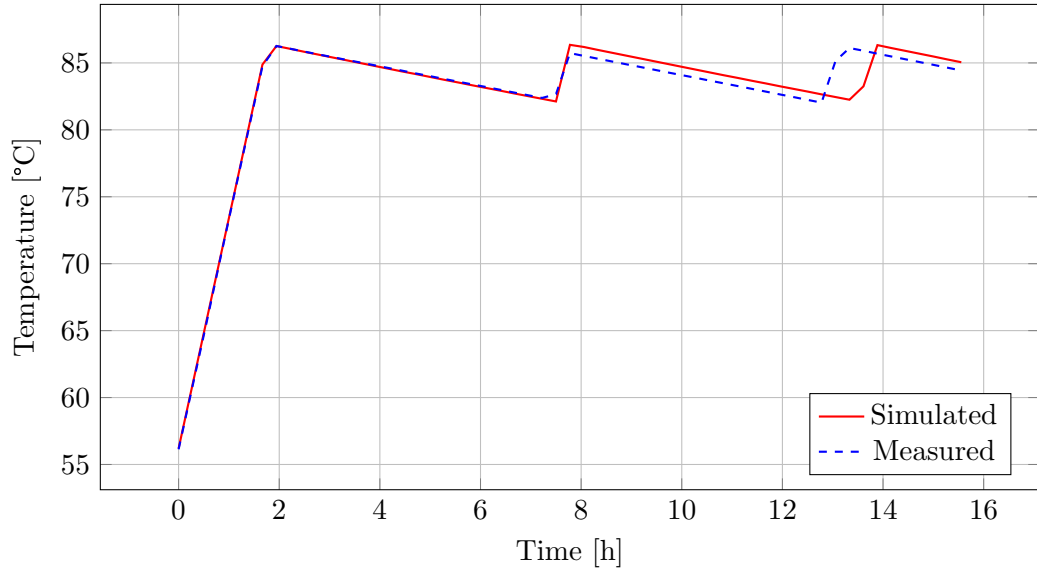


FIGURE 5.3: Comparison between measured water temperature and matching simulated water temperature.

5.2.3 Operational Duty Cycle

An important metric in the stable operation of a water heater is the amount of time that the element is on versus the amount of time that it is off, the ratio of this will be referred to as the 'duty cycle'. Adapting Equations 4.1 and 5.1 into Equations 5.2 and 5.3 allows us to solve for the time taken for the water temperature to increase or decrease between specific temperatures and thus determine the duty cycle, as in Equation 5.5.

$$t_h = \frac{(T_n - T_{n-1}) * m * c}{P} \quad (5.3)$$

$$t_c = \frac{-1}{r} \ln \frac{T_{n-1} - T_a}{T_n - T_a} \quad (5.4)$$

$$D = \frac{t_h}{t_h + t_c} \quad (5.5)$$

Where:

- t_h is the time taken to heat
- t_c is the time taken to cool
- D is the duty cycle

For the specific water heater in the experiments and the comparison simulation, it can be determined that the duty cycle is approximately 4.16%. However; this duty cycle changes depending on the average steady state temperature as well as various other characteristics of the water heater. Thus at an average temperature of 70 °C with all other parameters identical the duty cycle reduces to approximately 3.2%. One of the notable influences on the duty cycle would be if the water heater has additional insulation (known locally as a geyser blanket) which would increase cooling time and decrease duty cycle. The understanding of duty cycle is used later in this research to provide a relationship between a water heaters average power consumption and its average steady state temperature. It is particularly pertinent to the operation of the Statistical Controller in Chapter 6.

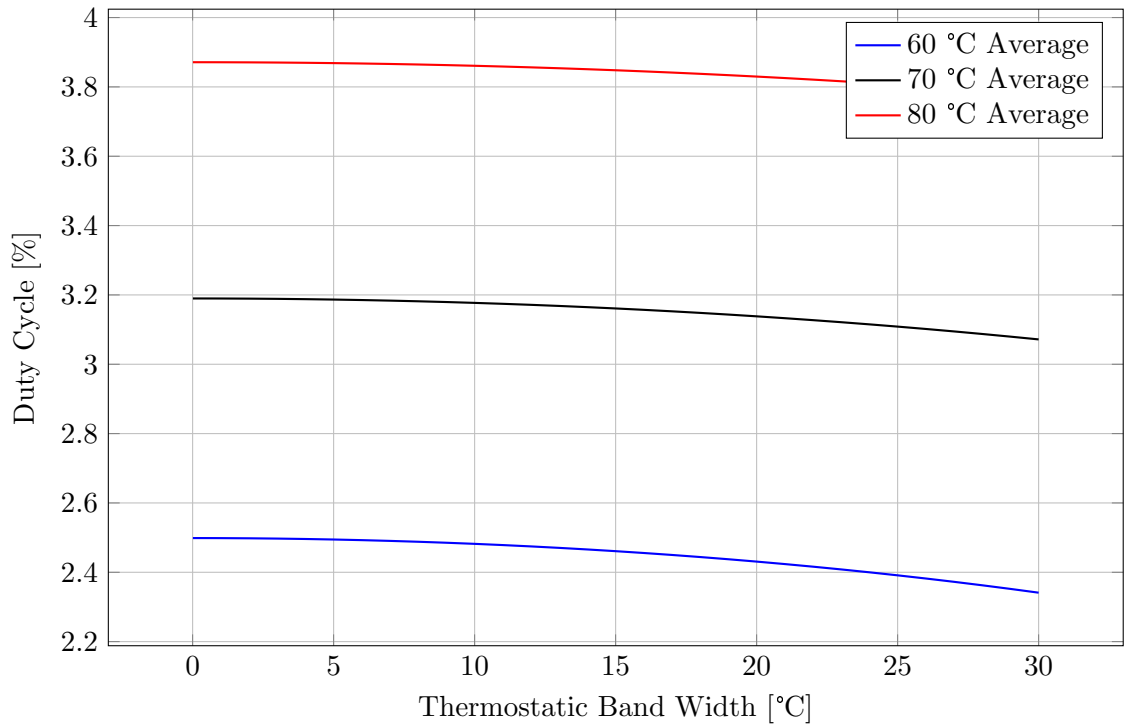


FIGURE 5.4: Approximate heater duty cycle based on average temperature and thermostatic band width.

Figure 5.4 above shows the variation of the duty cycle for the 100 litre, 2 kW water heater discussed in the rest of this Chapter. The y-axis shows the duty cycle while the x-axis represents how much the water temperature varies in standing operation, known as the thermostatic bandwidth. For example: a heater with an average of 70 °C that rises to 72 °C and drops to 68 °C would have a thermostatic bandwidth of 4 °C. As this bandwidth decreases the duty cycle increases, though the change in duty cycle is minimal in comparison to the impact that the average water temperature has.

5.2.4 Draw-off Operation and Thermal Stratification

When a water heater is in use, hot water is removed from the tank as it flows to a usage point. Because the water mains are a pressurised system, this means that cold water is introduced to the tank at the same rate that the hot water is removed. For an ideal system this means that the tank is divided into two bodies of water: heated water layered above and cooler water layered below. However because the flow of water into the tank is turbulent, some mixing of the water occurs. This results in a third body of water: the mixing layer. Figure 5.5 below shows the theoretical visualisation of these layers.

The layers thus formed begin to radiate heat between themselves as the water temperatures equalize. This further mixing does not occur uniformly and more layers of differing temperatures are formed. This is known as thermal stratification and the water in the tank develops a temperature gradient from cold water at the base of the tank to hot water at the top.

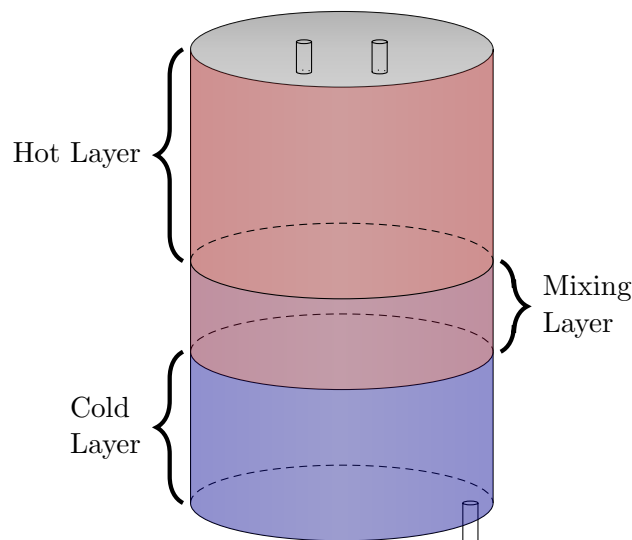


FIGURE 5.5: Layers of water in a vertical water heater.

5.3 Conclusion

The above Chapter has presented the idea of using thermal appliances to “store” energy as an alternative to batteries or pumped storage. The characteristics of water heaters allow them to be used as both dispatchable and deferrable loads without directly limiting service delivery. A simulated model for a typical water heater was developed and calibrated with physical tests.

Chapter 6

Control Algorithms

The Chapter below discusses the required operation of a controller designed to provide autonomous demand response through the control of water heaters. After generic requirements are discussed, two potential control paradigms are presented. The controllers use the grid frequency as an indication of grid strain and attempts to ensure this strain is eased while end users consistently receive hot water.

6.1 Control Requirements

As discussed in Chapter 2, the goal is to create a feasible controller for water heaters that will remove the heater load from the grid in times of strain, while acting as a dispatchable load when there is surplus supply. The following items are basic requirements of any controller implemented:

- The controller must be able to use a grid frequency measurement to determine the state of the grid and then respond in an attempt to improve the health of the grid.
- The controller must use temperature measurements to reduce any impact to end users and prevent damage to the heater tank.
- In a large scale implementation there must be enough variation in operation of the controllers (through either random elements or varied control limits) that multiple controllers do not continually switch on and off simultaneously, which would cause an oscillation of the grid frequency.
- The algorithm for control (as well as the acquisition of measurements) must be simple enough to implement on a low-cost microcontroller.

- The control must be self regulating: it must use the frequency to prevent too much load being added or removed from the grid.

Both the controllers presented below were developed to meet these requirements.

6.2 Dimensional Control

The first method for control that has been created for this dissertation is named Dimensional Control. This scheme can be understood as a visual mapping between the measured water temperature and grid frequency. Within this mapping there are defined bands of control which indicate whether the heater element should be turned off, turned on, or left unchanged. Figure 6.1 below shows the basic form of the controller.

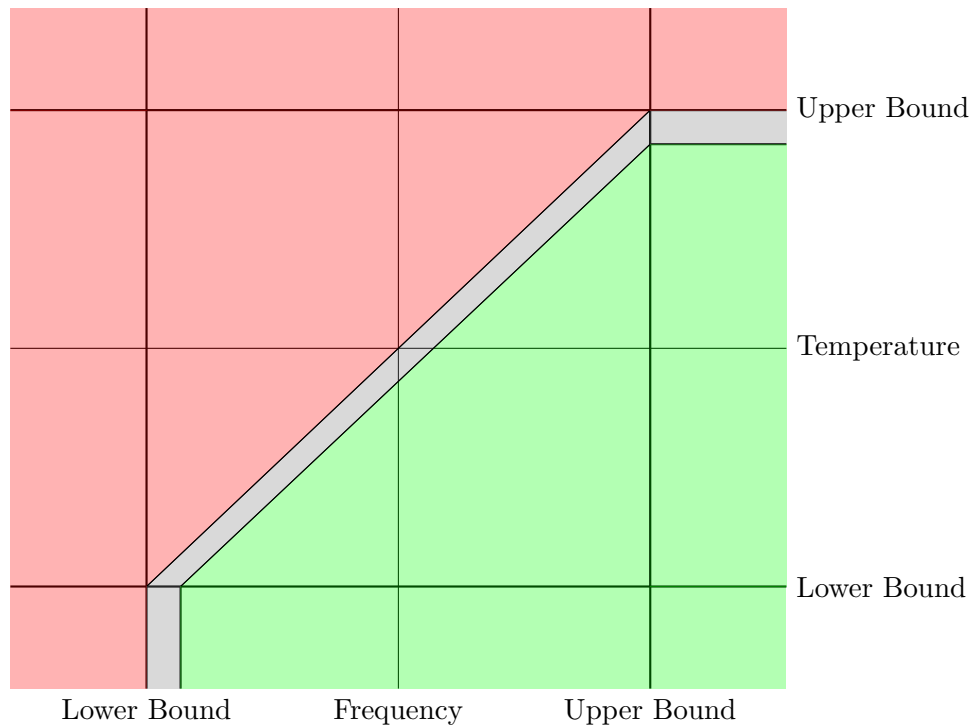


FIGURE 6.1: Template form of dimensional controller.

At any given point in time the measurements of temperature and frequency will indicate a specific point within this scheme: then the bands of control determine the controller's operation. In the green band, the element state is set to on; in the red band it is set to off and in the grey band the element state is unchanged.

Beyond this there are also points of safety inherent in the template at the limits of operation. As the temperature approaches an upper bound then, no matter how high the frequency goes, the upper temperature will not be exceeded: thereby ensuring that the

water is not heated to the point of damaging the tank. Similarly as the frequency reaches its lower bound, the water heater will turn off (no matter how low the temperature goes) in order to minimize the load on the grid even if it results in users not receiving hot water.

6.3 Statistical Controller

Perhaps a more elegant scheme for control, is the following proposed Statistical Controller. This method for control utilizes a probabilistic curve to determine the percentage chance for an individual water heater to turn on or turn off.

6.3.1 Linear Form

The most simplistic, linear form of this control can be found in Figure 6.2 below.

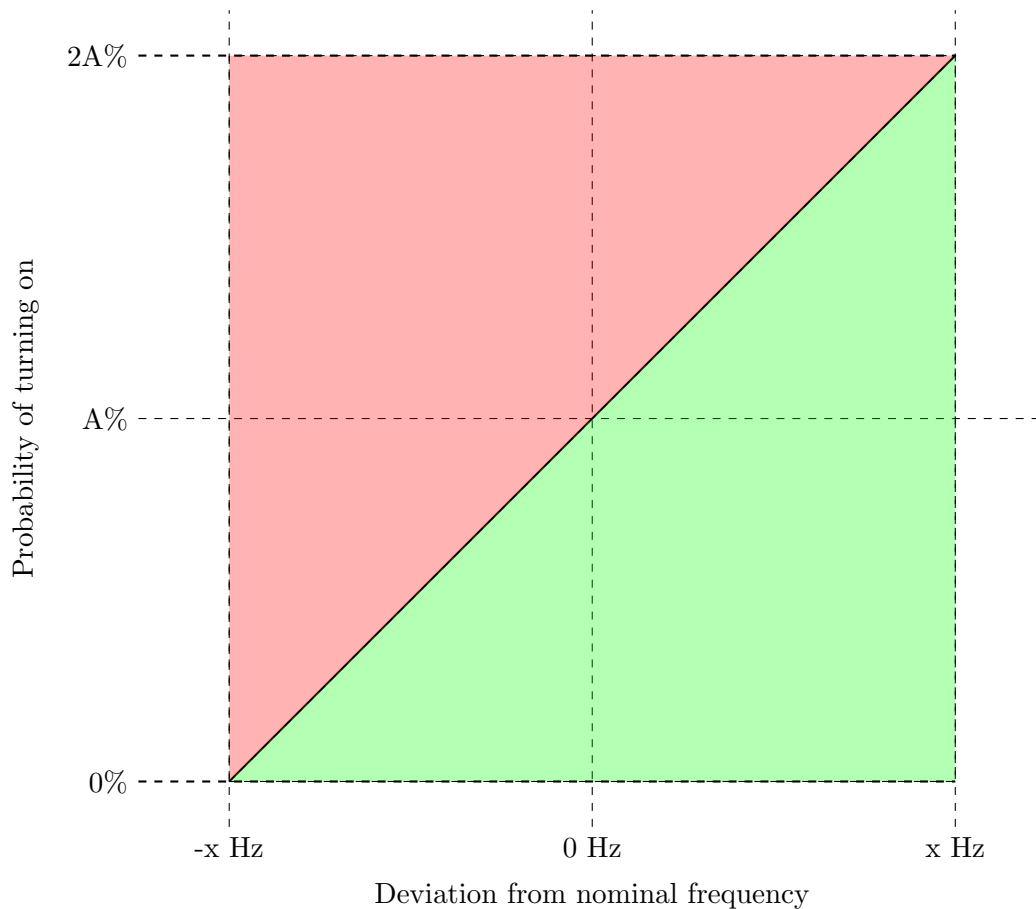


FIGURE 6.2: Template form of statistical controller.

Similar to the Dimensional Controller presented above; at any given point in time the grid frequency will deviate from the normal by a certain amount. A percentage is generated based on the current grid frequency that dictates the percentage time each water heater should be on for (the duty cycle). The “Alpha” value is the duty cycle required maintain a suitable temperature when the grid frequency corresponds to a 0 Hz deviation. The linear scaling between the frequency and percentage extends to a minimum of 0 percent at the maximum negative frequency deviation. This ensures that at times when the grid is strained (indicated by a drop in frequency) individual water heaters have less chance to turn on and thus at a grid scale more load will be removed as the heaters turn off. As the frequency increases above the nominal value it becomes increasingly probable for individual water heaters to turn on. When aggregated this increase of load on the grid will restore the frequency while usefully consuming the surplus power.

6.3.2 Internal Temperature Bias

To incorporate the need for users to receive hot water, a secondary manipulation can be applied that biases the percentages generated according to the water temperature. This biasing increases the percentage chance to turn on at low temperatures and decreases it at high temperatures. An example of this can be seen in Figure 6.3. This bias is actualized through a linear scale based on the maximum and minimum permitted temperature along with an absolute scaling factor. It can be seen that the original percentages based on the grid frequency still exist but now variations of the internal water temperature also impact the percentages generated.

6.3.3 Quadratic Reinforcement with Temperature Bias

Another change in the operation of the controller would be to add a form of reinforcement. Figure 6.4 below is in the same format as Figure 6.2 above, but the probability generated follows a quadratic trend. In comparison to the linear control, this reinforcement reduces the probability at frequencies close to the nominal and increases it at large deviations. The theory here is: first, that lower “spikes” of power will occur when the frequency is close to the nominal (because the change in probability is minimal); but second, at large deviations, the larger probabilities generated will restore the frequency faster (as more load is added or removed from the grid).

Once again the probability can be biased according to the internal water temperature, ensuring that higher temperature heaters are more likely to turn off and lower temperature heaters are more likely to turn on. This can be seen in Figure 6.5 below.

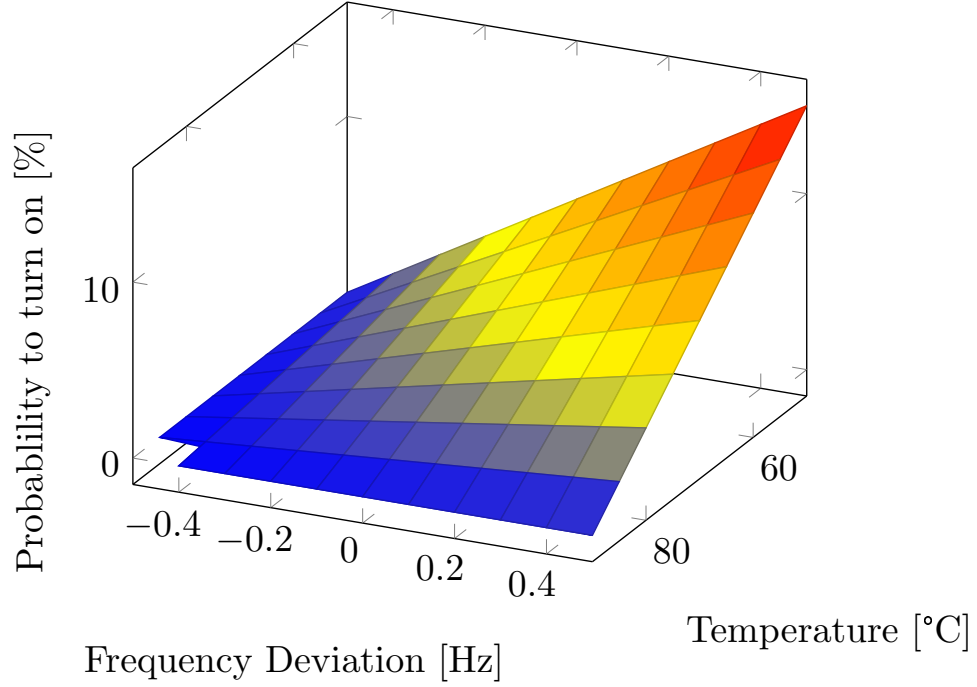


FIGURE 6.3: Plot showcasing the effect of internal temperature bias has on the chance to turn on with respect to water temperature and grid frequency.

6.4 Conclusion

This Chapter introduced two novel methods for controlling water heaters, using the grid frequency and internal water temperature. The Dimensional Controller operates by pre-defining operational regions for each water heater, it requires individual tuning to operate effectively which may limit largescale implementation. The Statistical Controller functions with probability to turn on for each water heater, this probability is determined from a defined relationship between the grid frequency and water temperature.

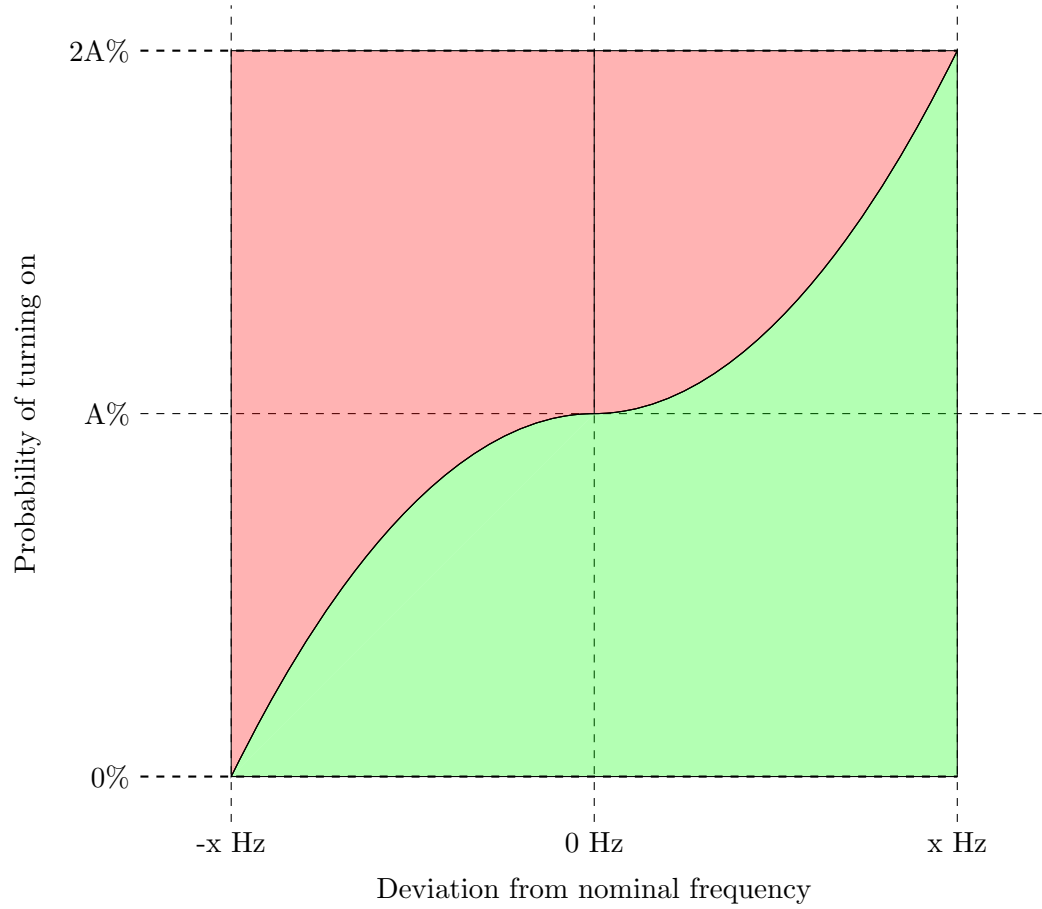


FIGURE 6.4: Template form of quadratic reinforcement for the statistical controller.

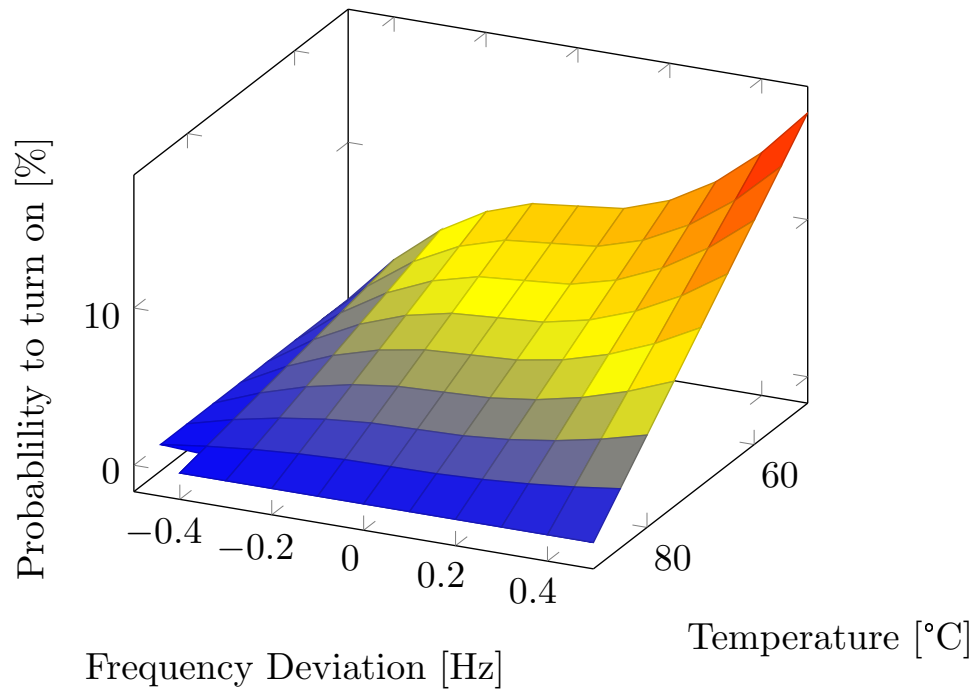


FIGURE 6.5: Plot showcasing the effect of internal temerature bias on a quadratically reinforced probability with respect to water temperature and grid frequency.

Chapter 7

Simulation Structure

To test the controllers, a simulation environment was created in Java to emulate a large number of water heaters connected to a grid. This Chapter details the structure and the logical flow of the simulation. Excerpts of the code utilised for the simulations can be found in Appendix C at the end of this document.

7.1 Standard Elements

There are three main classes that make up the simulation. These are interconnected in order to mimic the operation of controlled water heaters on a grid.

7.1.1 The Grid

The Grid class describes the characteristics and operation of a theoretical AC grid. Its parameters include:

- The grid frequency, which will be changing throughout the simulation.
- The stiffness of the grid, which can be understood as the inverse of the sensitivity of the grid frequency to changes in the power balance.
- The stable base load on the grid. If power is consumed above this base load the frequency will drop and if the power consumption is below this base load then the frequency will rise.
- The current time step of the simulation.

The Grid class also contains an ArrayList of “loads”: an expandable amount of unique objects that represent the controlled water heaters on the Grid.

The AdvanceState function of the Grid iterates through each of the loads and then: firstly calls the controller function which will turn the heater element on or off; and secondly calls the water heater function (which determines the water temperature change, given the element state). Within the AdvanceState function, the impact that changing loads have on the frequency is also calculated - using the stiffness of the grid. The methodology for this calculation, to determine the new frequency, is detailed further in the sections below.

7.1.2 Loads/Controllers

The loads in the ArrayList are essentially interfaces between the Grid and the actual heaters. Each load is connected to a single water heater and contains all the control parameters and control algorithms. This allows the individual controllers to turn the water heaters on or off independently from each other, based on the state of the Grid and the water temperature.

The design and implementation of the two types of controllers is presented in the Chapter 6 as well as in Appendix C. A polymorphic type structure allows for different controllers to be developed and used with ease. For practical purposes, any controller created will need to use the grid frequency and the water temperature, although other control parameters could typically include maximum and minimum permitted water temperatures and desired frequency deviation, as seen in the control schemes presented in the previous Chapter.

7.1.3 Water Heaters

The WaterHeater class acts as a model for any water heater connected to a controller on the Grid. All water heater objects created have the parameters required to model their standing operation, namely:

- The volume of the water within the tank in litres.
- The power of the heater element in kW.
- The current temperature of the water.
- The ambient temperature of the air surrounding the tank.

- The convection coefficient describing the rate at which heat is radiated to the surroundings.
- The state of the heater, indicating whether the element is on or off.

With these parameters in place, the simulated water heater model can use the thermodynamic equations presented in Chapter 5 to determine the current temperature of the water given that the element is on or off.

7.2 Controller Algorithms

7.2.1 Dimensional Controller

The Dimensional Controller discussed in Chapter 6 is actualised within the simulation with basic comparative checks. Using the measured frequency and water temperature: first the Dimensional Controller checks if the measured point is above the threshold to turn off (above the upper bound of the hysteresis); second it checks if the measured point falls below the threshold for turning off (below the lower bound of the hysteresis). If neither of these actions occur, the Dimensional Controller concludes that the grid and heater are within the hysteresis band and the state of the heater does not change. Next the controller makes safety comparisons against the minimum frequency and maximum temperature allowed, to ensure that at low frequencies and high temperatures the heater turns off.

7.2.2 Statistical Controller

To manage the Statistical Controller, a threshold is generated based on the controller parameters and the current grid frequency (this threshold is the line dividing the on and off state in the visual representation in Figure 6.2). A randomly generated number is then compared to this threshold and if the random number falls above the threshold then the heater is turned off (and if it falls below the threshold, the heater is turned on). In the case with internal temperature biasing (as presented in Chapter 6) the threshold generated is scaled by a function of water temperature to ensure that it is more likely that lower temperature water heaters are turned on while higher temperature ones are turned off. As with the Dimensional Controller: the safety bounds are checked to ensure no under-frequency or over-temperature events occur.

7.3 Logical Flow

7.3.1 Initialisation

A modular initialisation is required so that a wide variety of scenarios can be simulated without altering the core characteristics of the elements, this is the reason for the distinct initialisation pattern discussed below.

In the most basic form, the initialization is as follows: a distinct Grid is created with its desired parameters; then specific water heaters can be created and linked to their own controllers and added to the grid. Beyond that, the set-up has many possible configurations. For example, multiple unique grids can be created; multiple loads can be created autonomously in bulk with identical or random parameters; specific parameters can be altered to determine their impact and significance.

7.3.2 Reading and Writing Data

During the simulation, a real world grid frequency is read in from a text file. This frequency data was obtained from measurements of the South African grid during April 2015. Samples were taken at one second intervals with millihertz precision and then filtered into the ten second intervals used in the simulations and seen in Figure 4.2 in Chapter 4. An hour of the per second data can be seen in Figure 7.1 below.

The following results are written to a text file at every step of the simulation: the time step number; the power consumption of the loads; the grid frequency as changed by the variable load; and then the instantaneous temperature of each water heater. Each piece of data is comma delimited and each simulation step is delimited with an end-line. This makes the analysis of the data easier, as it can be exported into Matlab or Excel in a CSV format.

7.3.3 Controlling the Loads on the Grid

At each time step of the simulation, each controller is looped through and its form of control is implemented. Based on its control parameters and these measurements, each controller turns its connected heater either on or off. In either case the Grid object stores the amount of power that is then added or removed from the grid. Once all heaters have been controlled, the power difference between the heaters and the base load dictates the change in frequency through the stiffness of the grid. This frequency change (due to controlled loads) is then averaged with frequency measured from the real grid, this is

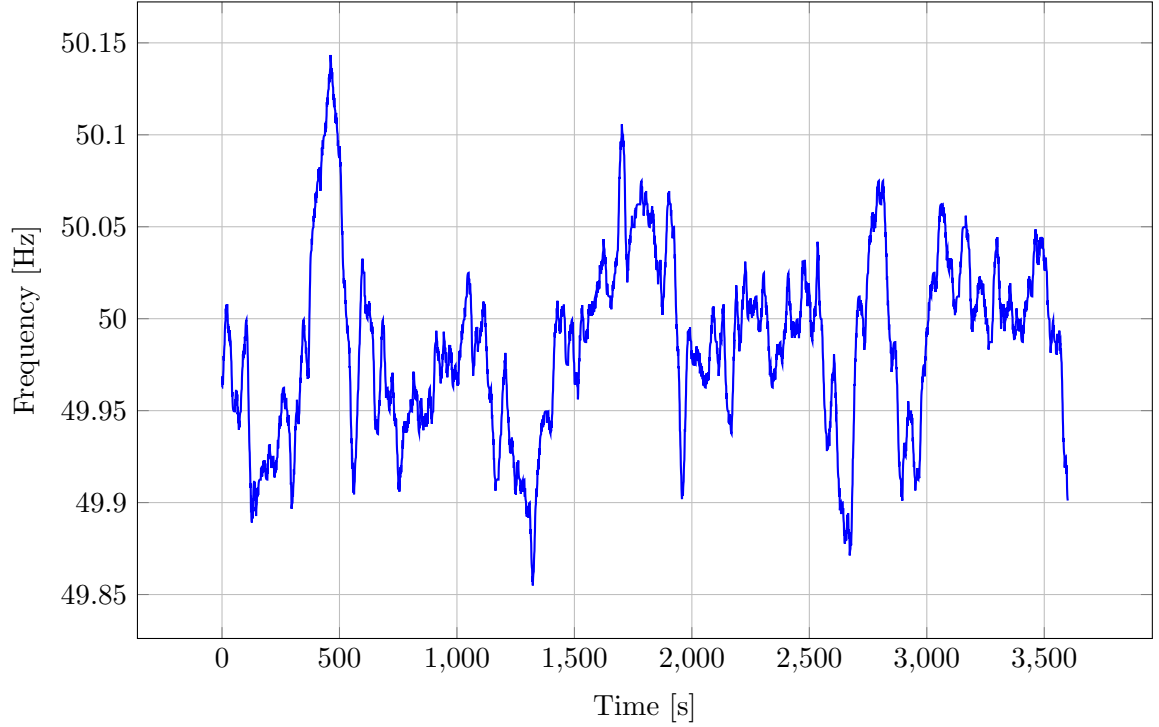


FIGURE 7.1: Sample of the measured frequency used within simulations

done to produce psuedo-random frequencies that represent the random nature of users turning on and off loads throughout a grid. Even though the averages obtained through this method may result in frequencies outside of permitted ranges for both the grid and the controllers, it showcases the ability of the controllers to regulate the frequency.

7.3.4 Simulation Paradigms

Various paradigms are set up in order to fully test the controllers. In each case, the initialization and mathematical operations may vary. Notable variations could be changing the number and type of loads on the grid; the grid stiffness or the manner in which grid frequency is altered by the controlled loads changing; Specific use cases could also be specified (as shown with water draw-offs). In the next Chapter, the changes made for each type of simulation are made clear because the changes cause drastic variations in the functioning and analysis of the simulation.

7.4 Conclusion

This Chapter has presented the basic structure of the simulations performed, as well as detailed descriptions of each element within the simulations. A Grid object populated

with controllers and water heaters is iterated through in time, while the controllers dictate the switching of each connected heater. Models for both the grid and water heaters were obtained through literature and thermodynamic laws.

Chapter 8

Simulation Results and Analysis

The Chapter below details specific simulations run in order to test various aspects of the controllers. The effect of changing the control parameters of the Dimensional Controller is shown, and then a large scale simulation with the Dimensional Controllers is presented. This large scale simulation attempts to determine the impact that implementing such a control scheme would have on both the grid and on users. Simulations with Statistical Controllers showcase these controllers ability to maintain individual water temperature while reacting to a changing grid frequency.

8.1 The Dimensional Controller

8.1.1 Modes of the Dimensional Controller

A simulation was run with the goal of finding the effect a Dimensional Controller has on the functionality of a water heater. Each water heater was created with identical characteristics, the 100 litre, 2 kW model developed in Chapter 5. The three temperature profiles in Figure 8.1 show a comparison of basic modes of operation for the Dimensional Controllers. The red curve shows standard thermostatic control (as physically tested), while the black curve and the blue curve show the simulation results of a relaxed and a stringent controller.

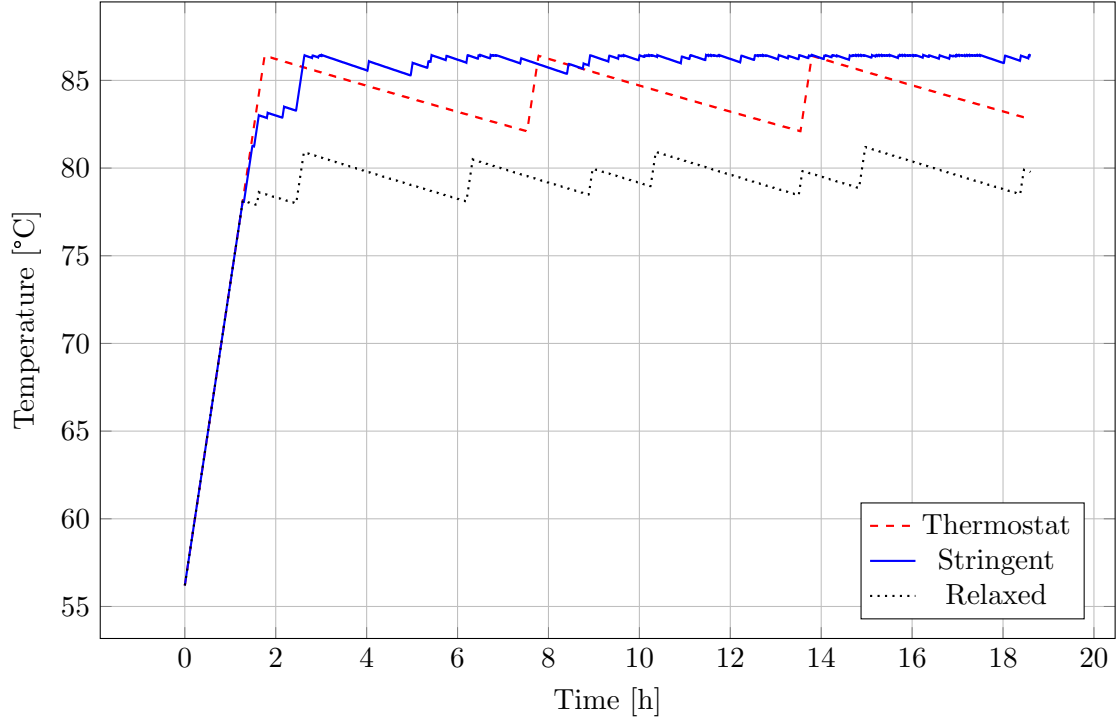


FIGURE 8.1: Comparing the simulated temperature profiles generated by differing control parameters to the measured temperature profile seen through standard thermostatic control.

The stringent controller acts as a regulator: it consumes power while the grid runs normally to ensure that the water temperature is as high as possible. This means that during extended periods of grid strain there is unlikely to be a loss of service delivery. The relaxed controller provides greater bands of deviance, occasionally resulting in lower temperatures and the risk of losing service. But it consumes less energy in comparison to both the thermostatically and stringently controlled heaters due to it maintaining a lower average water temperature. Table 8.1 details the control parameters used to create the two dimensional controllers and the thermostatic parameters.

TABLE 8.1: Dimensional Controller Parameters used for Mode Comparison

	Thermostat	Stringent	Relaxed
Lower Frequency	N/A	49.5	48
Upper Frequency	N/A	50	50.5
Deadband	N/A	0.15	0.3
Lower Temperature	82.1	55	55
Upper Temperature	86.4	86.4	86.4

8.1.2 Monte Carlo Type Variation of Dimensional Controllers

The simulation detailed below generates multiple water heaters with identical characteristics that are connected to unique controllers. The simulation determines the impact the controlled heaters have on the grid frequency and on expected water temperature.

8.1.2.1 Key Parameter Variations

Table 8.2 below details the ranges and differences between the unique controllers created, which amounts to around 1400 individual controllers and water heaters. All the water heaters were created identical to the model developed before, based on physical experimentation.

TABLE 8.2: Monte-Carlo type Dimensional Controller parameter ranges

	Minimum	Maximum	Increment Size
Lower frequency	49.0	49.6	0.04
Upper frequency	50.0	50.8	0.2
Deadband	0.1	0.3	0.04
Lower temperature	50	60	1
Upper temperature	80	90	1

8.1.2.2 Non-controlled Comparable Simulation

It is necessary to create a base scenario in order to observe the impact that the controllers have on the simulated grid. To achieve this, the same number of simulated water heaters were created with normal thermostatic control. These had randomised lower and upper temperature bounds that ranged between 75 °C and 80 °C and 85 °C and 90 °C respectively. The initial water temperature was also randomised to between 77.5 °C and 82.5 °C.

Creating this simulation gives us an indication of what the power consumption would look like for standard water heaters. This consumption profile can be seen as the black graph in Figure 8.3. It forms a steady base load that fluctuates randomly, as expected. This load averages around 270 kW, which is used in the Monte Carlo type simulation as the grid base load to offset the frequency feedback.

8.1.2.3 Frequency Feedback

As discussed: the grid stiffness is used to determine the impact that the changing load has on the frequency throughout the simulation. In the presented simulation the sensitivity

was set to 0.00025 Hertz per kilo-Watt (*i.e.* a stiffness that indicates a change of 4000 kW of supply or consumption would cause the grid frequency to change by 1 Hz), as it was found that the stability of the grid frequency was hindered with higher sensitivity.

8.1.2.4 Results

There are two sets of results to analyse. The first set is the water temperature observed in the water heaters throughout the simulation. The second set is the power consumption and the effect on the grid frequency.

The aggregated water tank temperatures during the simulation are depicted in the histograms in Figure 8.2 below. They show the percentage of water heaters with certain minimum, maximum and average temperatures for the simulation period.

The reason histograms were chosen to display and analyse the water temperature data, is that (with every controller having different parameters) random samples would not be an accurate representation. Considering the large number of water heaters, it would also not be feasible to visualise the temperature profiles of all the heaters at once.

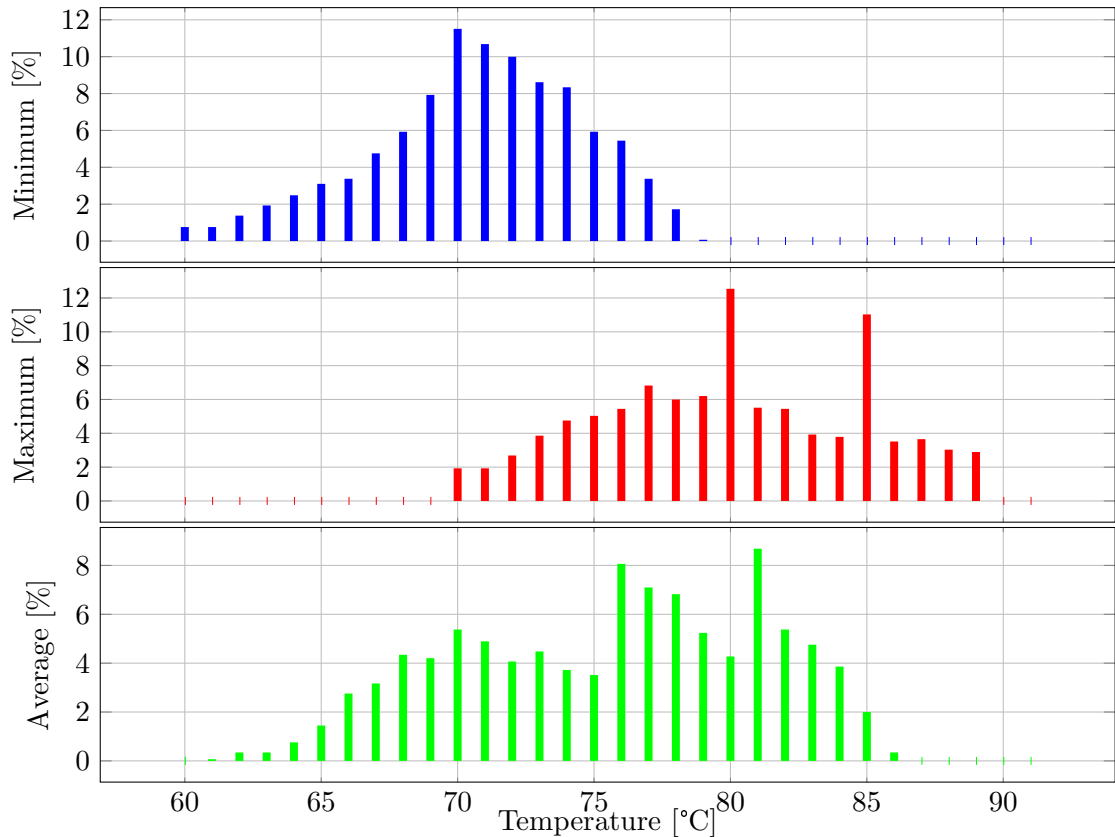


FIGURE 8.2: Range and occurrence of minimum, maximum and average water temperatures in the simulation.

All the minimum temperatures fall under 80°C as this is the maximum initial temperature for all the water heaters. The majority of water heaters remain at temperatures higher than 70°C . The peaks seen in the maximum temperature histogram are artifacts arising from the hard set upper temperature limits that the majority of the created controllers have. The peaks correspond to the temperatures 80°C and 85°C , as expected. The average temperatures range between 60°C and 86°C , with the majority falling between 75°C and 85°C . The data inferred from these histograms indicates that throughout the simulation all controllers maintain the water at a usable temperature, as the lowest recorded temperature is 60°C .

As mentioned above, the second set of results to be analysed involves the power consumption and the grid frequency. This data is displayed below in Figure [8.3](#)

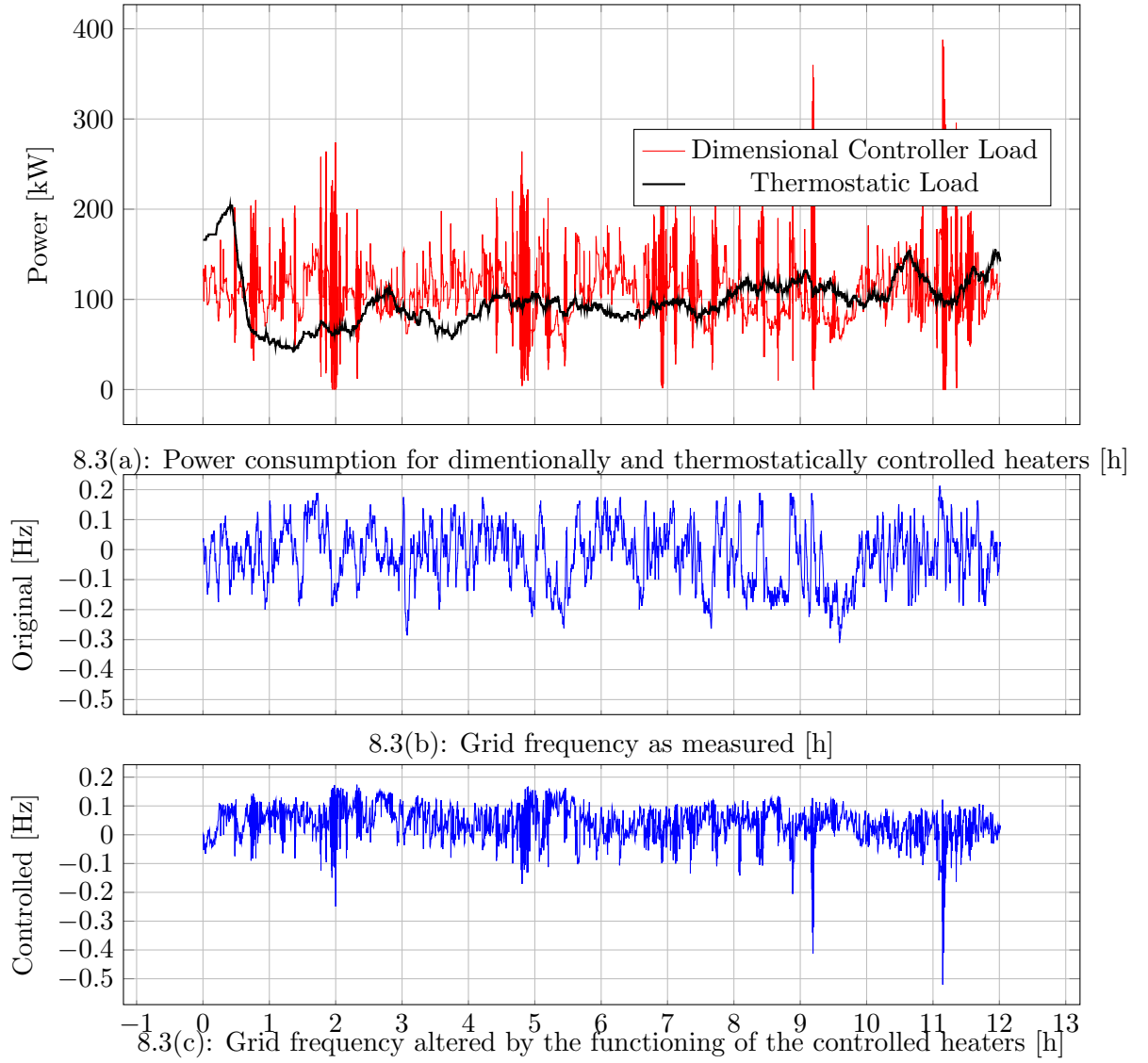


FIGURE 8.3: Power consumption comparison of thermostatically controlled and dimensionally controlled heaters with grid frequency over a period of around 3.5 hours.

The impact the dimensional controllers have with respect to the grid frequency is clear. With high frequencies there is larger power consumption, indicating that many of the heaters are on at certain times. With low frequencies most (and sometimes all) of the heaters turn off. The power consumption of the thermostatically controlled heaters (determined through the simulation discussed in Section 8.2.2) can also be directly compared to the power consumption of the dimensionally controlled heaters. It can also be seen how the original, measured grid frequency is regulated by the controllers. The controlled frequency deviates less from the nominal frequency, though there are points of sudden drops that indicate a limitation in the functioning of the Dimensional Controllers.

The time magnified plot in Figure 8.4 below shows the staging effect of the controllers. As the frequency changes the heaters turn on and off in proportion to the deviation from the nominal frequency.

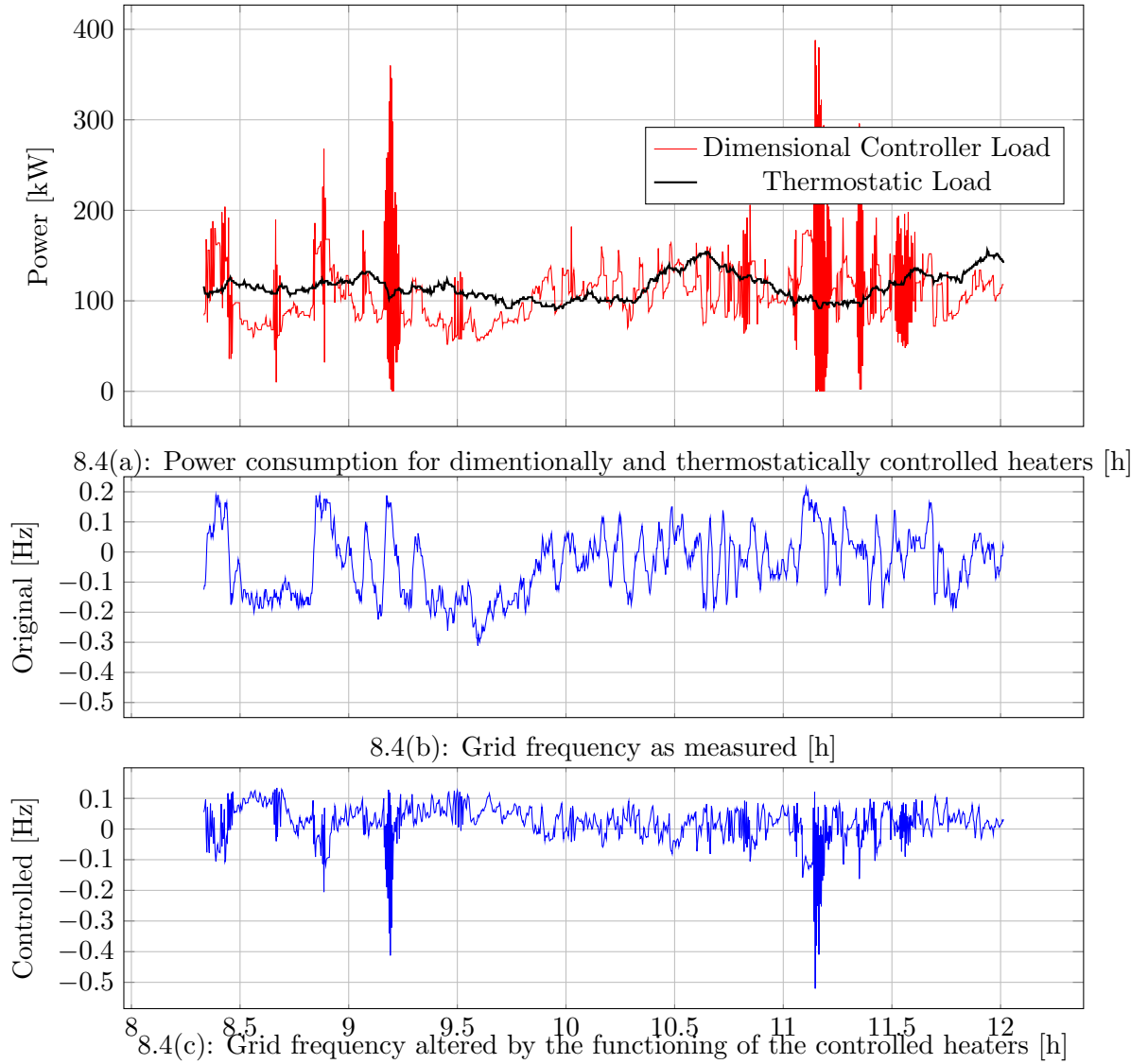


FIGURE 8.4: Time magnified power consumption of simulation compared to grid frequency.

The impact the controllers have on the frequency can be seen more distinctly in Figure 8.5 below. Here the original and modified frequencies are compared through a histogram representation of the frequency deviation from 50 Hz.

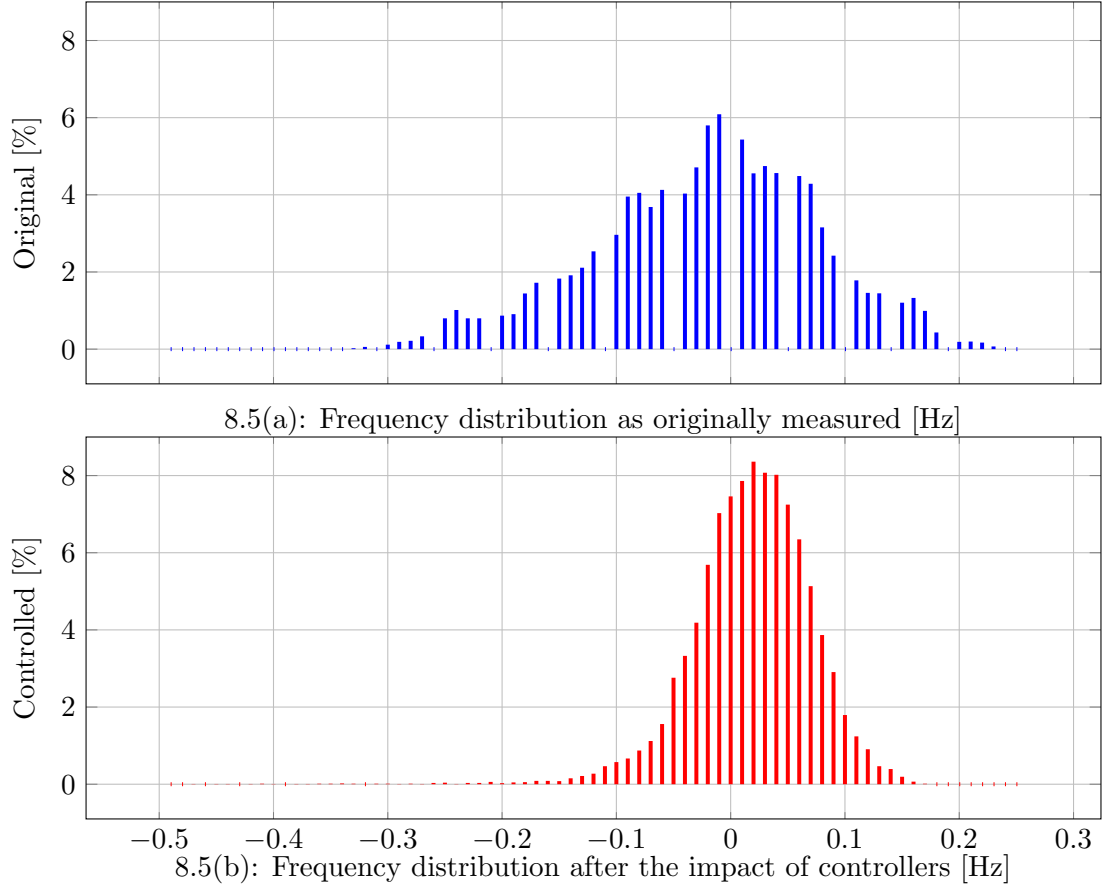


FIGURE 8.5: Distribution of grid frequency deviation from 50Hz with and without controllers.

8.2 Statistical Control

Running the simulation with statistical controllers is more simplistic, as all the heaters and controllers can be made identical by design. With identical heaters and controllers the analysis is made easier and can also be generalised.

8.2.1 Key Parameter Variations

To achieve the results that are presented below, certain key parameters of the simulation elements are changed to represent various cases.

The number of water heaters in the simulation is not changed; in every variation there are specifically 1000, 2 kW water heaters that are being controlled. The base load is initially set to a value that approximates the power consumption removed by the controlled heaters. In this case there are 1000 standard heaters that have been replaced, and since the duty cycle has been approximated as 3.2%, then on average approximately

64 kW would be consumed. If the controlled water heaters cumulatively consume more or less than this base load, it is an indication that there is a power imbalance on the grid and the frequency will change accordingly. The base load can also be altered during the simulation in an attempt to emulate a change in load elsewhere on the grid, which would cause a power imbalance.

Once again, the grid stiffness parameter is needed to determine the impact that any imbalance has on the frequency. Knowledge of the system operation allows the insight that a lower stiffness indicates that the heaters form a large portion and thus any imbalance will cause larger deviations of the frequency. Conversely, a higher stiffness (with the same imbalance) will cause a smaller frequency deviation.

On the controller side, both the Alpha percentage value and the permitted frequency deviation can be altered to change the statistical generation. Within the simulations presented here, the Alpha percentage will be set to 3.2%. This ensures that (at the nominal frequency) water heaters will maintain a steady temperature around 70 °C. If there were a variety of water heaters with different duty cycles, this Alpha parameter would change on a case by case basis. The permitted frequency deviation is selected to restrict the frequency: a lower value would reduce how much the frequency could deviate from the nominal frequency, but would also reduce the flexibility of the controllers, potentially resulting in non-suitable water temperatures. A greater value for the permitted deviation would have the opposite effect: suitable water temperature would be more reliably reached, but the stability of the grid may suffer as the frequency fluctuates further than can be sustained.

8.2.2 Internal Temperature Bias Impact

To test the impact that the temperature biased controller has, we look at the temperature profiles of 15 random water heaters (a sample from the full simulation) over the course of 4.5 days. In Figure 8.6 below it can be seen that the heaters with biased control (above) reach the steady state temperature faster than the standard statistical control (below).

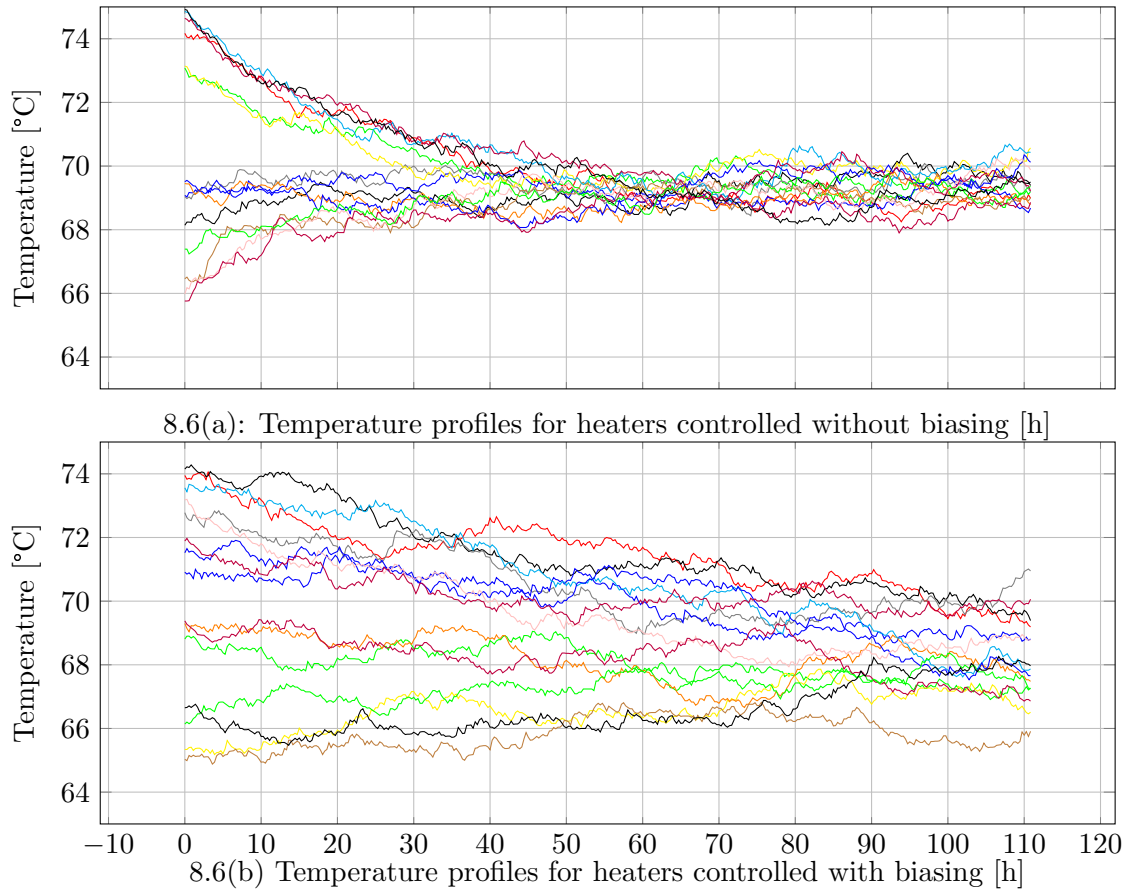


FIGURE 8.6: Water temperature change in time, showing the impact of biased statistical control for 15 sample water heaters.

The fact that the temperatures all tend toward a stable point around 70 °C proves that our Alpha value selection (based on the stable duty cycle) is correct. It follows that a higher Alpha would raise the steady state temperature while a lower one would decrease it.

8.2.3 Varying Base Load

Running the simulation with a varying base load shows how the controllers respond to a power imbalance on the grid. In the simulation presented below, the base load was increased or decreased every ten thousand seconds. Figure 8.7 below show the impact a changing load has on the typical water temperature of stable heaters. With the knowledge of how the steady state temperature relates to the duty cycle of a water heater, it can be inferred that the overall consumption of the controlled water heaters is changing in response to a changing base load. Once again the 15 heaters presented below form a sample of the total tested in the simulation.

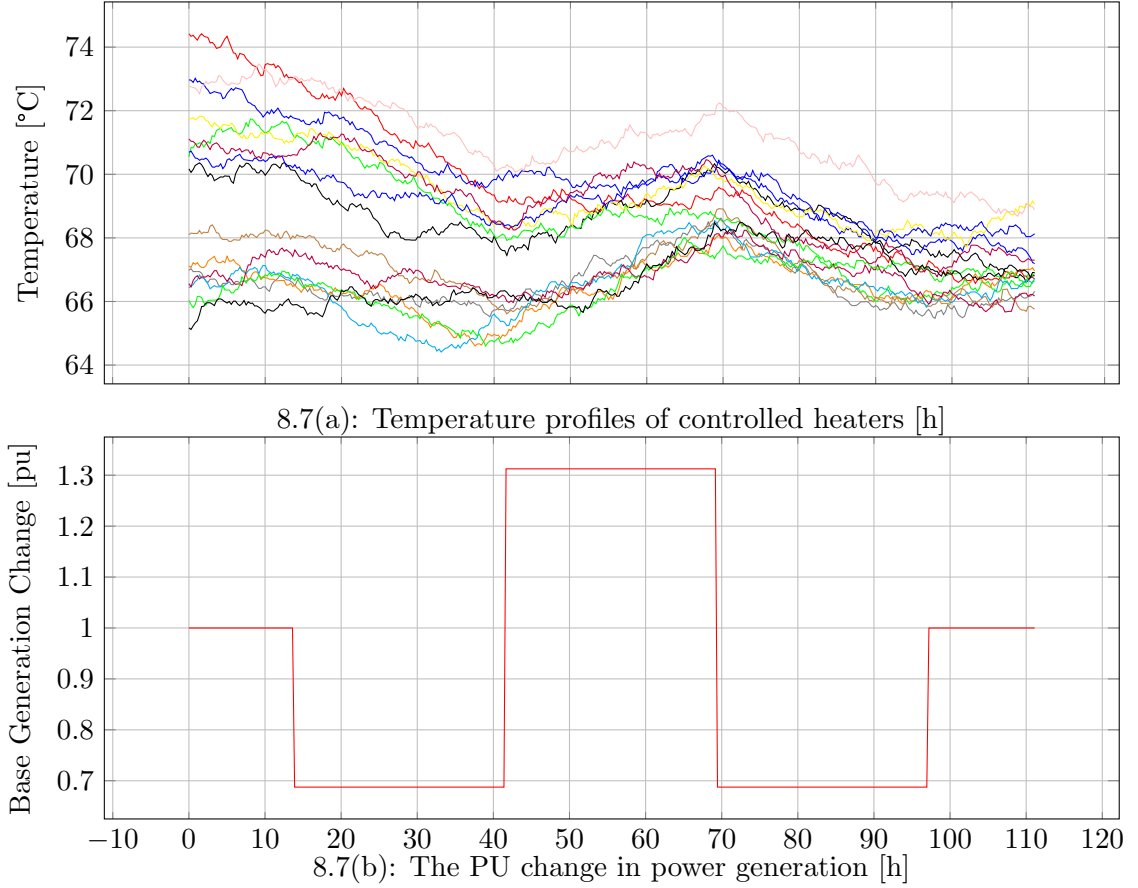


FIGURE 8.7: Water temperature change in time, with a base generation capacity changing per unit for 15 sample water heaters.

8.2.4 Water Draw-off Emulation

Emulating a user drawing off hot water can be seen in Figure 8.8, where the temperatures of two water heaters drop by approximately 30 °C over a short period of time. One water heater drops straight while the other has a smaller step drop before a larger drop. In both cases the water temperature returns above 50 °C in about an hour and above 60 °C in about two and a half hours, showing a reliable return to usable temperature and (once again) the impact of bias control for lower temperatures.

8.2.5 Impact to Grid Frequency

With the water heaters changing the load on the grid, it is pertinent to show the impact that the controllers have on the grid frequency. A sample of the typical frequency can be seen in Figure 8.9, where the differences between the measured frequency, a high stiffness grid, and a low stiffness grid are shown. A noteworthy observation is the fact that while the controllers are successful in reducing the typical frequency deviation, there is an

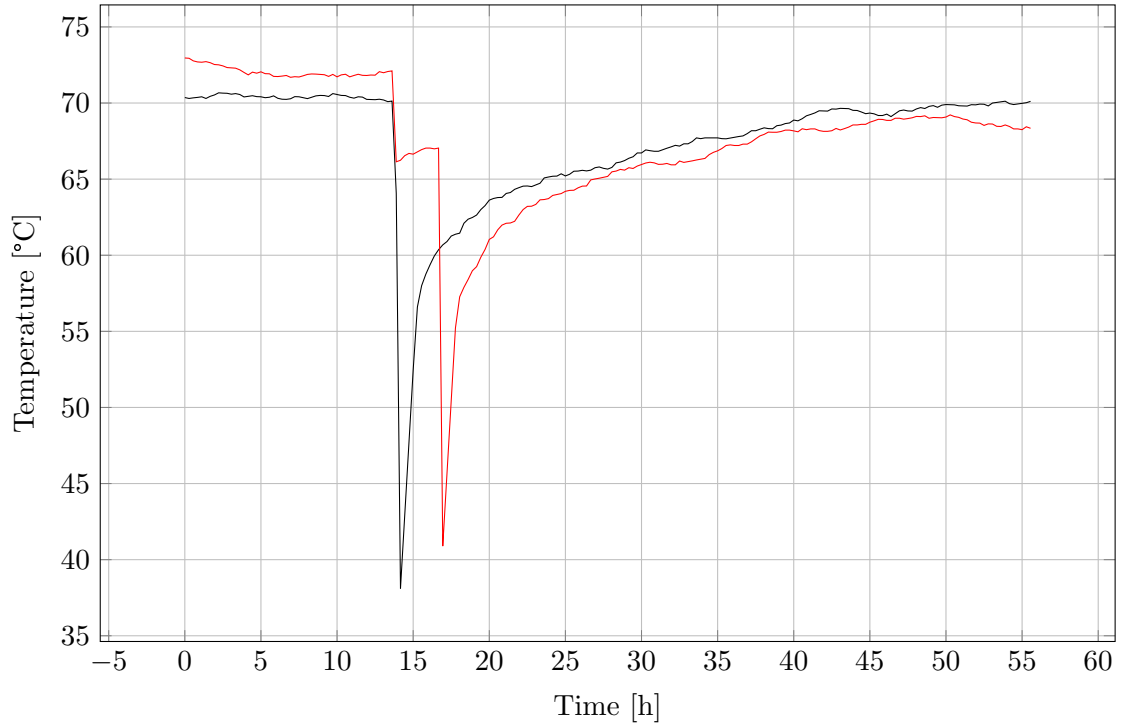


FIGURE 8.8: Water temperature change in time, showing the impact of water draw-off.

element of noise that can cause large instantaneous deviations - particularly in the case of high sensitivity.

Figure 8.10 below allows us to see various distributions of the grid frequency, and the impact that the grid stiffness has is clear. At a low stiffness there is minor improvement, while a high stiffness stabilises the frequency notably. It is also clear that the resulting frequency follows a normal distribution closely (this is expected, as the random function used in the controllers is normally distributed). The minor deviations from this distribution can be attributed to the random nature of the measured frequency, as well as the impact of the temperature biasing aspect of the control.

8.3 Conclusion

The purpose of this Chapter was to highlight the results of specific simulation paradigms, both with Dimensional and Statistical Controllers. Results with both variations show viability: ensuring heaters remain at useful temperatures, and changing power consumption patterns in response to changing grid frequency. Perhaps the most notable aspect of the simulations is the stiffness of the grid, varying only the stiffness can alter the stability of the simulation greatly.

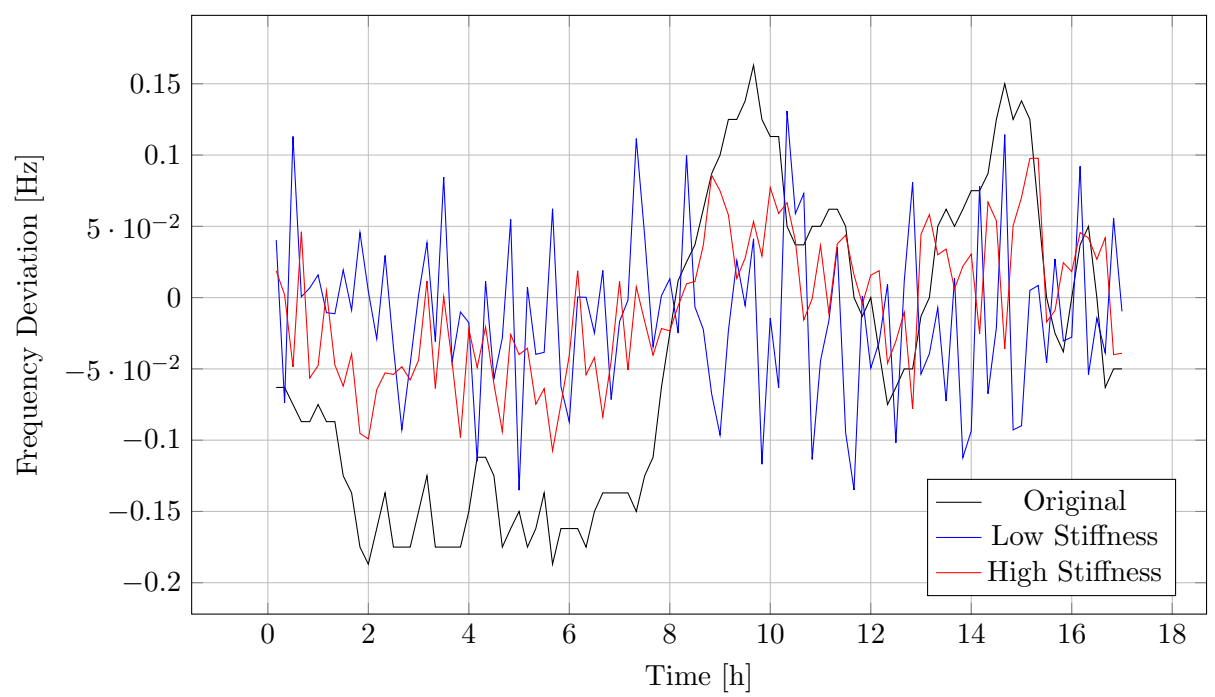


FIGURE 8.9: Typical grid frequencies centered around 50 Hz for varied stiffness compared to measured data.

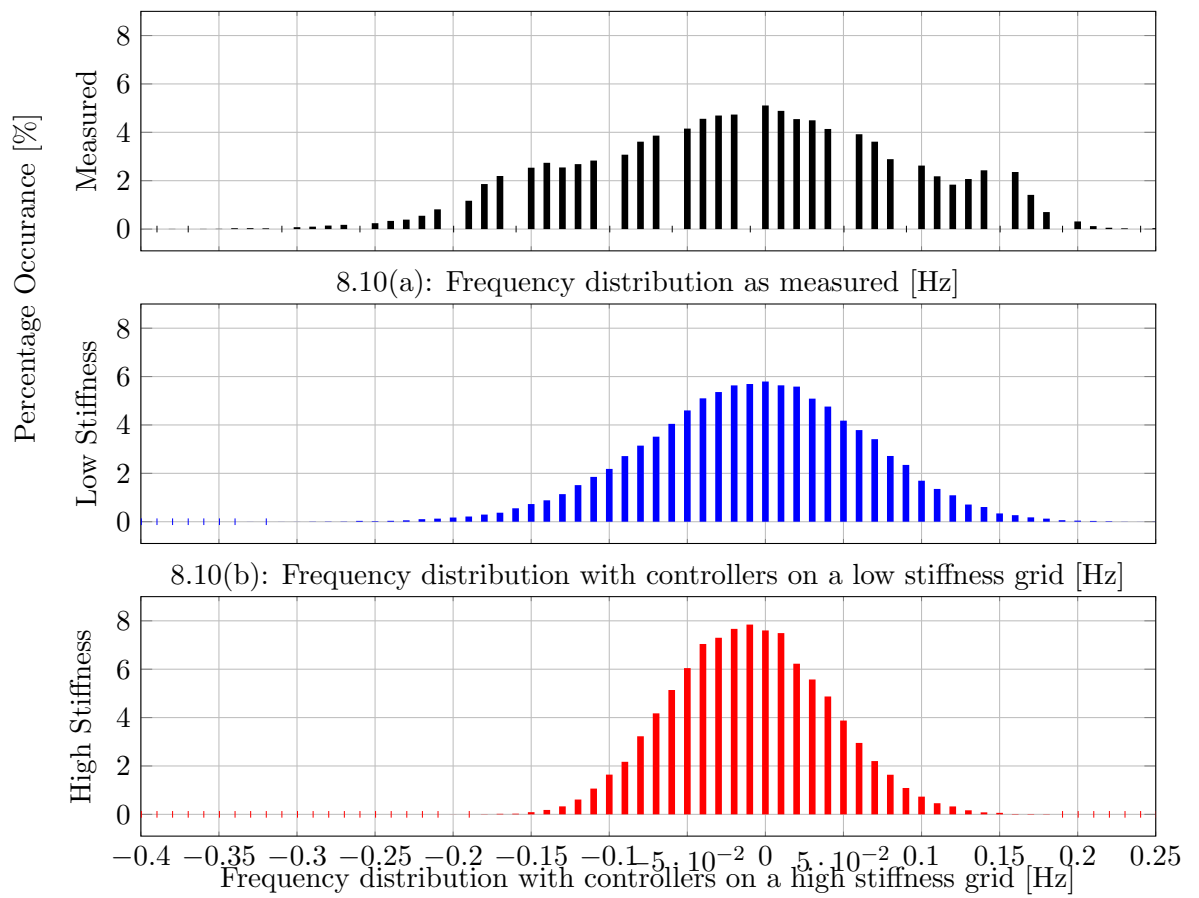


FIGURE 8.10: Frequency deviation distribution depending on grid stiffness compared to measured frequency data.

Chapter 9

Discussion of the Research

In this Chapter, the results found throughout the research are discussed in terms of feasibility, limitations and what future research could focus on.

9.1 Core Findings

The differences between the two control schemes, as well as a further understanding of flexible loads, are discussed below.

9.1.1 Comparing the Presented Control Schemes

Both of the developed controllers operate in a similar manner: turning on or off only if measured conditions are met. The Dimensional Controller is implemented with an understanding of the desired frequency deviation and temperature bounds, which means that it is intuitive to select the control parameters. The Statistical Controller requires a deeper understanding of water heater duty cycle, to ensure that heaters remain at usable average temperatures.

At a large scale level, the Statistical Controller is simpler to implement, as the key parameters relate to all controlled devices with the same characteristics. Conversely, the Dimensional Controller requires tuning and variation, as discussed in the Monte-Carlo type simulation, to ensure that power consumption does not begin to oscillate and harm the grid.

9.1.2 Considering Realistic Flexibility

Chapter 5 briefly discusses the flexibility of individual water heaters. The logic behind the Statistical Controller allows for a much broader and generic understanding to be developed for the flexibility of a controlled water heater. From the results in Chapter 8 it is seen that the Statistical Controller operates by decreasing or increasing the duty cycle of each water heater, as a means to decrease or increase the load on the grid. The duty cycle percentage of each heater can be used to indicate the overall power consumption percentage, by using the law of large numbers. Changing the steady state duty cycle also results in changing the steady state temperatures. Figure 9.1 below shows how the duty cycle determines the average water temperature (calculated with the standard 100 litre, 2 Kw heater parameters used in this dissertation). At the lowest usable temperature of 50 °C, the duty cycle is approximately 1.79 %; and at the highest useable temperature of 90 °C, the duty cycle is around 4.54 %. It follows logically that if water typically remains at 70 °C (a duty cycle of 3.18 %) then the combined controlled heaters can defer 1.39 % of their total load and dispatch 1.36 %. It must be noted that these sample values will change notably for cases of different water heaters and determining even approximate values is non-trivial when there is a combination of varied heaters.

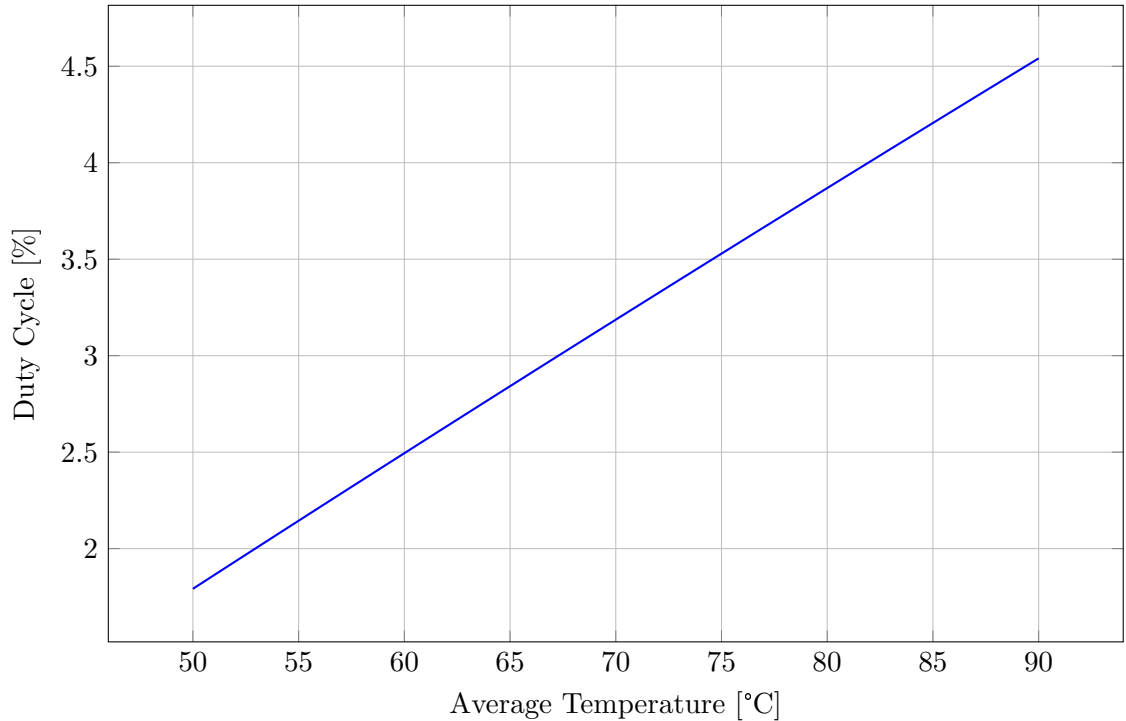


FIGURE 9.1: Approximate heater duty cycle based on average temperature.

9.2 Practical Limitations of the Research

While it has been shown in simulation that the autonomous control of water heaters can be used to regulate the load on a grid, there are practical aspects that limit the usefulness of such a system working in reality.

9.2.1 Grid Frequency in First World Countries

It was proposed that an autonomous system could be utilized even in first world countries to regulate load. An immediate challenge to this is the inherent stability of the grid in first world countries. In Figure 9.2 below it can be clearly seen how the grid frequency in Germany (as measured in April 2016 in the city of Paderborn) deviates notably less from the nominal than in South Africa. With lower fluctuations, any controller developed would need to be more sensitive and respond faster (than an equivalent controller in South Africa) in order to function suitably.

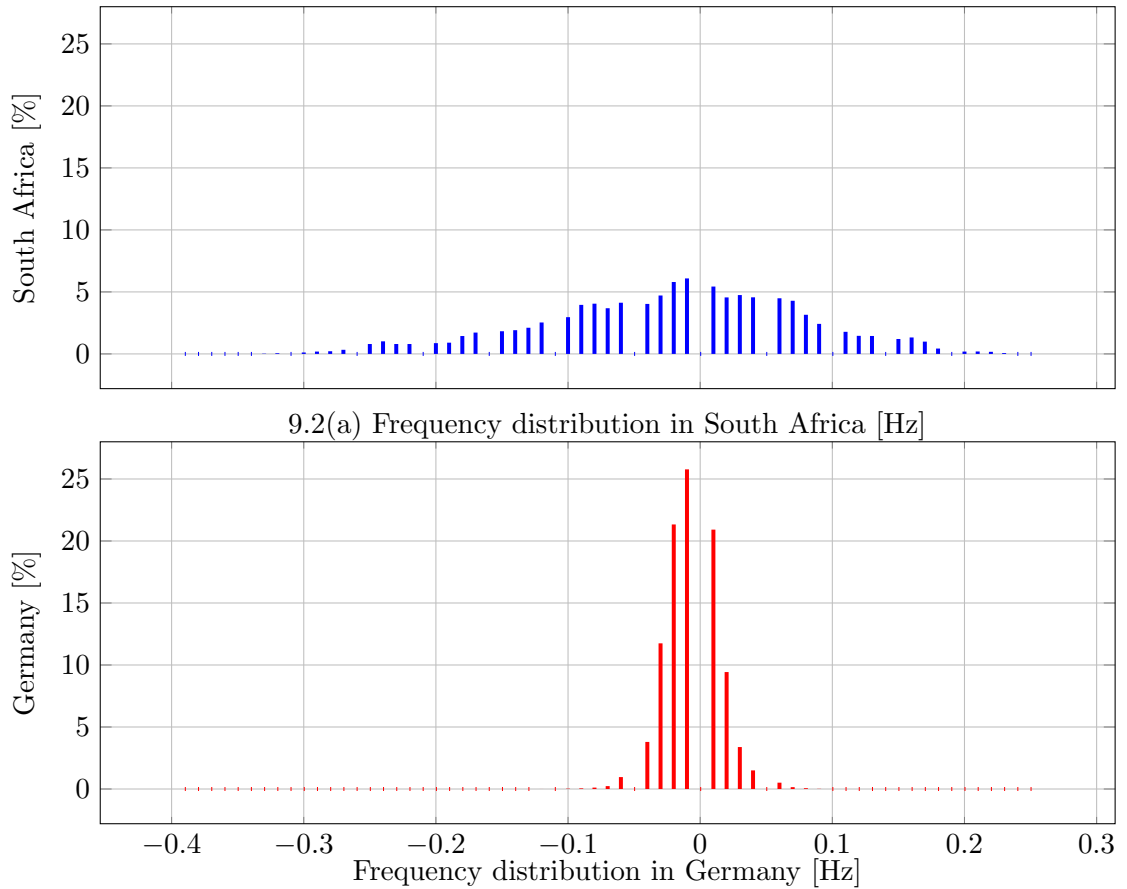


FIGURE 9.2: Distribution of grid frequency around 50 Hz: South Africa compared to Germany.

9.2.2 Physical Difficulties with Continuous Control

Under thermostatic control, water heaters typically will only turn on and off perhaps a dozen times in 24 hours. With either of the controllers presented above, it is possible for any heater to turn on or off hundreds or even thousands of times in the same period (because measurement and control happens multiple times a minute). While it is this fast response that makes the control viable in reacting to frequency changes, it is possible that this high number of switches could have negative impacts.

The first is the time to failure for the mechanical relays that switch the heater element. By increasing the number of switching operations a hundredfold, the expected lifetime of those switches is drastically reduced. Which, in turn, will raise the expense of running such a system. The use of solid state relays may improve the lifetime of switches but at a higher initial cost.

The second potential problem comes from switching large loads onto the grid continuously. The repetitive surges in current may damage the stability of the grid, particularly on small grids where any changing consumption is not negligible.

9.3 Further Research

Below are some thoughts on the direction that future research in this area could take.

9.3.1 Limited Water Heater Model

A key deficit in the research done here is that realistic water draw-off and heater stratification was not included in the simulations. The basic water draw-off (done by decreasing the water temperature over a period of time) does not take into account the semi-random nature of water usage throughout a day, nor does it take into account the thermal stratification of the water within the tank. Further research should thus seek to incorporate a statistical model for typical household water usage. Also, the water heater model should be improved to accurately represent any thermal stratification that occurs.

9.3.2 Analog Power Control

As the research stands, the controllers developed can only effect a water heater by turning it on or off. This binary control greatly reduces the flexibility of any scheme implemented. A controller that can vary the actual power consumption of a heater

would allow for more precise control of individual loads and perhaps even mitigate the difficulties with continuous control discussed above.

Potential methods for actualizing this would lie within the power conversion domain. Power converters (such as a four quadrant converter or buck converter with rectification) could provide the heater element with variable DC power. Lower cost and less precise alternatives could be in the form of externally commutated converters utilising thyristors (similar to a light dimmer circuit); though the harmonics caused through such a phase-based control may limit the viability of such control.

9.3.3 Micro-Grid Test Bed

To further prove the capabilities of the control paradigms presented in this research, physical testing is needed. An isolated micro-grid would be suitable, as the limited number of sources and loads could be controlled more easily than the large number on a full-scale utility grid. The capabilities of the controllers to improve grid stability could be tested at the boundary condition of a small grid with a low stiffness.

9.3.4 Additional Control Parameters

It may be possible to improve the operation of an autonomous demand response control scheme by incorporating more measurements. Noting voltage fluctuations could give an indication of the local loading on the grid, as dropping voltage would indicate a large current draw. The rate of change of frequency could also provide insight into the intensity of the strain on the grid, though it would be heavily dependent on the natural inertia of the system.

In terms of non-grid measurements, some more user specific intelligence could be added to the controller. The ambient temperature could be used to pre-determine the length of time a water heater will remain hot for. Recording usage patterns would also assist in ensuring service delivery, while reducing load consumption.

More research and experimentation would be needed to determine if any of these additional control parameters would be feasible and useful to implement. Feasibility would also need to consider the cost implications of the various options, compared to the low cost of the controllers developed in this dissertation.

9.4 Conclusion

This Chapter has compared the controllers developed in this dissertation and discussed their practical limitations. In summary, while the work done operates as a proof of concept, there are factors that would limit its effectiveness in the real world. Potential directions for furthering the research have also been noted.

Chapter 10

Conclusion

The aim of the research presented here was to determine if simplistic control of water heaters, based on grid frequency measurements, could be a method to provide autonomous demand response on an AC grid. In comparison to research already undertaken in this direction; the work done here attempts to reduce the cost of implementing demand response by removing the dependency on Smart Grid technology, and focuses on ensuring users receive service from controlled appliances. The benefit of providing such control is two-fold: firstly, a large flexible load on a grid improves stability in the form of frequency regulation. Secondly, the usage of water heaters (defined as dispatchable and deferrable loads) allows the controlled load to form a notable portion of the total load and to minimally disrupt service delivery. Work previously done in this direction includes: attempts to use domestic appliances as an emergency load that can be added or removed from the grid; various control schemes meant for implementation as distributed load control; and the modeling of water heaters.

After discussing and generating basic models for both an electrical grid and a water heater, two types of controllers are proposed. Both controllers aim to alter the operation of individually connected water heaters through measurements of the water temperature and the grid frequency. Essentially the controllers seek to autonomously turn the attached heater off if the frequency is low and turn it on if the frequency is high. Additional temperature biasing is used to ensure that users still receive hot water. The Dimensional control scheme functions with a direct scaling between frequency and temperature: as the internal temperature increases, the heater will turn off at low-frequency events close to the nominal frequency; while lower temperatures require larger deviations below the nominal, for the device to turn off. The Statistical controller operates by generating a “percentage chance” to turn on which is based on the grid frequency; this chance is then scaled by an internal temperature bias, ensuring that a heater at

low temperatures has a higher chance to turn on and at high temperatures has a lower chance. Because the water heater duty cycle directly affects steady state temperature, the percentage chance to turn on (at the nominal grid frequency) should be selected such that a normal temperature is expected. With a large amount of statistically controlled heaters on the grid, their power consumption (at any given point) can be approximated with the chance to turn on.

A generalised simulation structure was created that allows for customisable scenarios of water heaters and controllers on a grid. Simulations were run to test the viability of the two types of controllers in certain scenarios, all using physical measurements of the South African grid frequency. With a wide variety of Dimensional Controllers in a Monte-Carlo type simulation, all heaters maintained a suitable water temperature and provided improved frequency regulation. However, it is noted that this is only possible with a high grid stiffness and thus the success of the results is debatable. Results from simulations with the Statistical Controller also show both suitable water temperatures and some frequency regulation. Again the frequency regulation is heavily dependent on the grid stiffness selected. The statistical controller shows promise as it responds effectively both to changes in grid power consumption, as well as simulated water draw-offs.

The research is discussed, and while the presented controllers show feasibility (the Statistical Controller more so than the Dimensional Controller) there are limitations to the usability of both controllers in reality, and the accuracy of the simulations presented. Future work should focus on better modelling a grid, as well as practical implementation on a small scale micro-grid test bed.

Appendix A

Water Heater Experimentation and Frequency Measurement

A.1 Introduction

This Appendix serves as a lab report for the experimentation done on the water heater test bed at The University of the Witwatersrand. The physical set up; the measurement equipment; the experiment methodology; and the results of the tests done, are detailed below. Beyond the water heater experiments, the tool and method for recording grid frequency is also detailed. Segments of the data presented are from work done by Mrs Y. Yen (University of the Witwatersrand), used and shown here with permission.

A.2 Physical Set Up

A test platform was installed in the Genmin Lab at the University of the Witwatersrand that allows for easy manipulation of, and access to, water heaters being used in experiments. The platform can be seen from a distance in [Figure A.1](#) below.



FIGURE A.1: Test bed for water heater testing.

The water heater tanks on this platform can be positioned either vertically or horizontally, as seen in Figure A.2 and Figure A.3 respectively. It also allows for the inlet water pressure to be controlled through an inlet regulator as seen in A.4 below.



FIGURE A.2: Vertical setup.

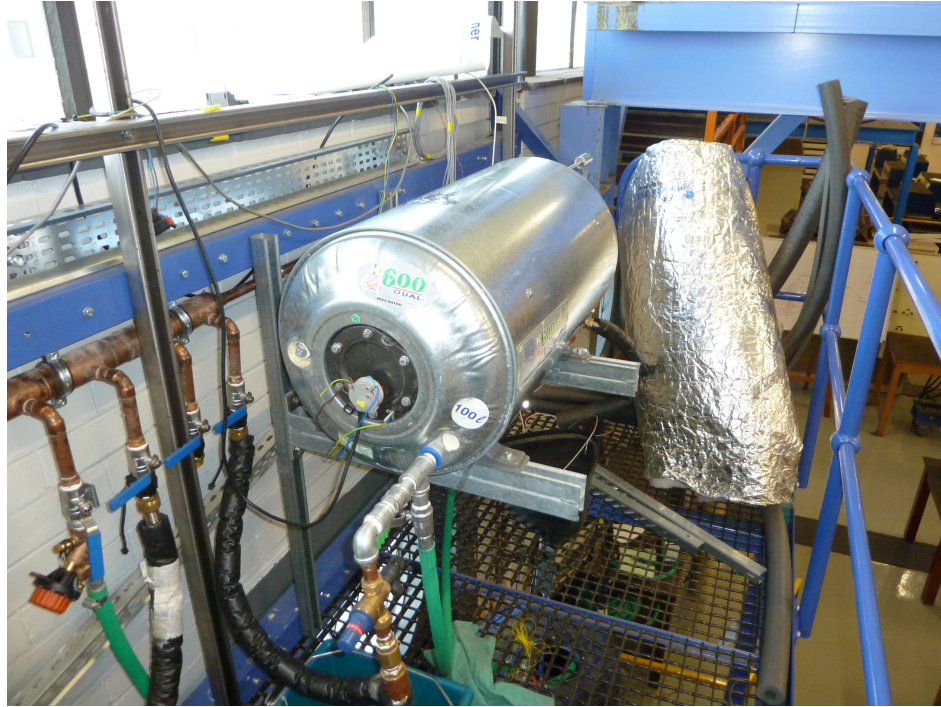


FIGURE A.3: Horizontal setup.



FIGURE A.4: Water inlet pipe with pressure regulator.

With the heater mounted in the desired orientation, temperature sensors can be inserted into the tank to directly measure the water temperature or positioned around the tank to measure ambient temperature. A custom made flange and connector are used to

insert the sensors while maintaining the pressure within the tank. The outlets of the water heater allow for temperature sensors to be fed in as well as a system to control the flowrate of water draw off. The outlet and various systems can be seen in Figure A.5 below.

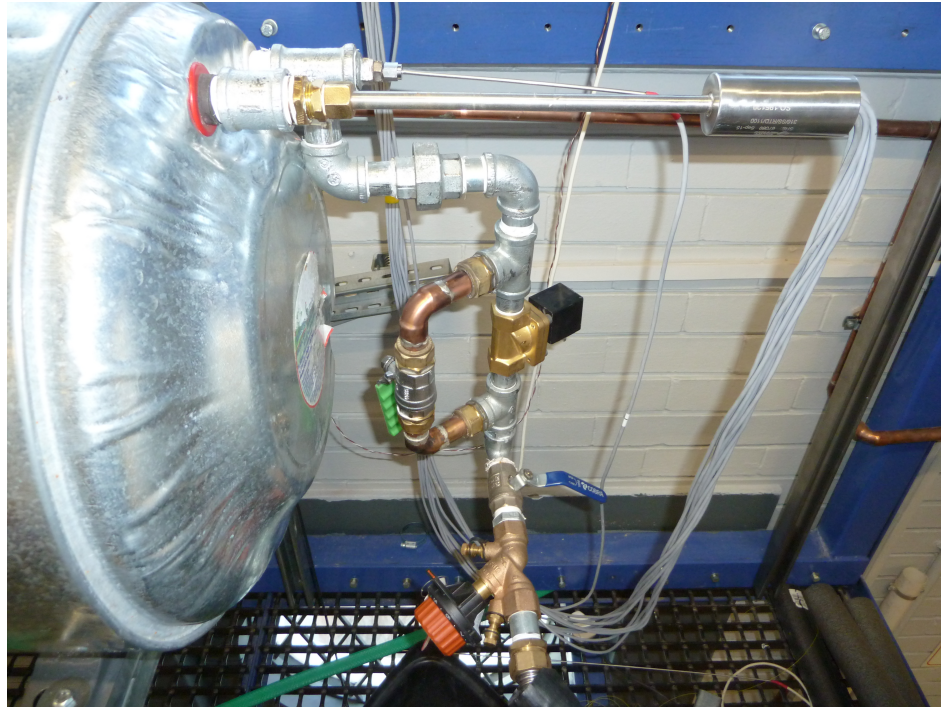


FIGURE A.5: Draw-off control and temperature sensors connected to water heater.

An inverter and battery bank were incorporated into the electrical distribution system to ensure that measurement systems could still run in the case of a power outage. The inverter and distribution box can be seen in Figure A.6 below (along with a Siemens PLC, planned to be used for automation in future to automate some of the experiments done).



FIGURE A.6: Electrical distribution box and inverter.

To allow for multiple tanks on the platform, there is a water distribution system that can provide water for up to 4 tanks (shown in Figure A.7).



FIGURE A.7: Water distribution to multiple water heaters.

A.3 Measurement Equipment

PT-100 RTDs were used throughout the tank to measure temperature. These temperature dependant resistors were connected to an Agilent Data-logger. A closed core current-transformer was used to measure the consumption of the heating element (this was also connected to the Data-logger). Figure A.8 below shows two different lengths of PT-100 sensors used during the testing.



FIGURE A.8: Two PT-100 temperature sensors used in the experiments.

Figures A.9 and A.10 show an approximation of the temperature sensor positions within the tank when in vertical and horizontal orientation. The sensors run close to the tank wall to avoid the heating element and use a secondary outlet as the point of entry.

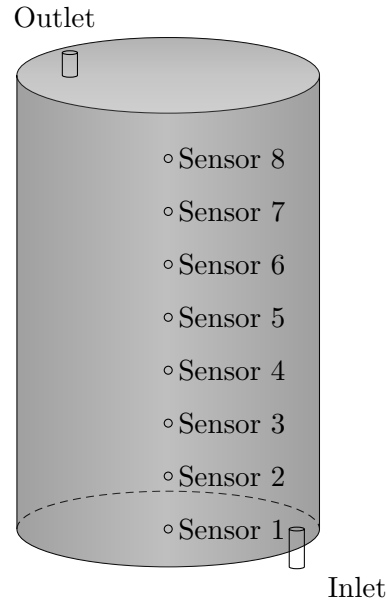


FIGURE A.9: Sensor positioning vertical orientation.

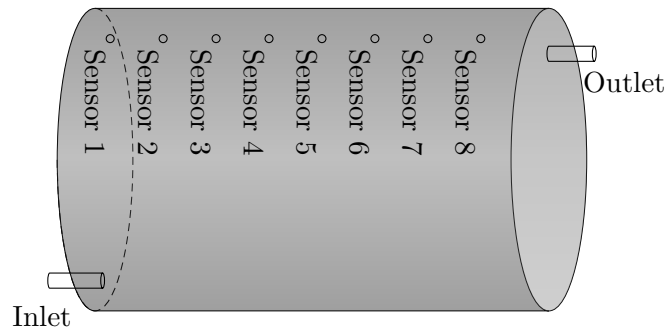


FIGURE A.10: Sensor positioning horizontal orientation.

A.4 Methodology

To begin with, the tank was drained of water so the temperature sensors could be positioned inside the tank. Once the tank was sealed again, it could be filled and pressurized with water. The thermostat of the heater was set to the desired temperature: in the case for all the tests done here, the temperature was set to 70 °C.

For standing loss tests, the water heater was turned on and left to run for the full duration of the test with no further interaction. For tests with water draw off, technicians controlled the water flow rate with the outlet valve, and measured the volume with a connected load-cell beneath the tank.

A.5 Results

A.5.1 Horizontal Test

Figure A.11 below shows the water temperature cycling in steady operation. Due to the positioning of the string of sensors within the tank, there is little deviation in the measured temperature.

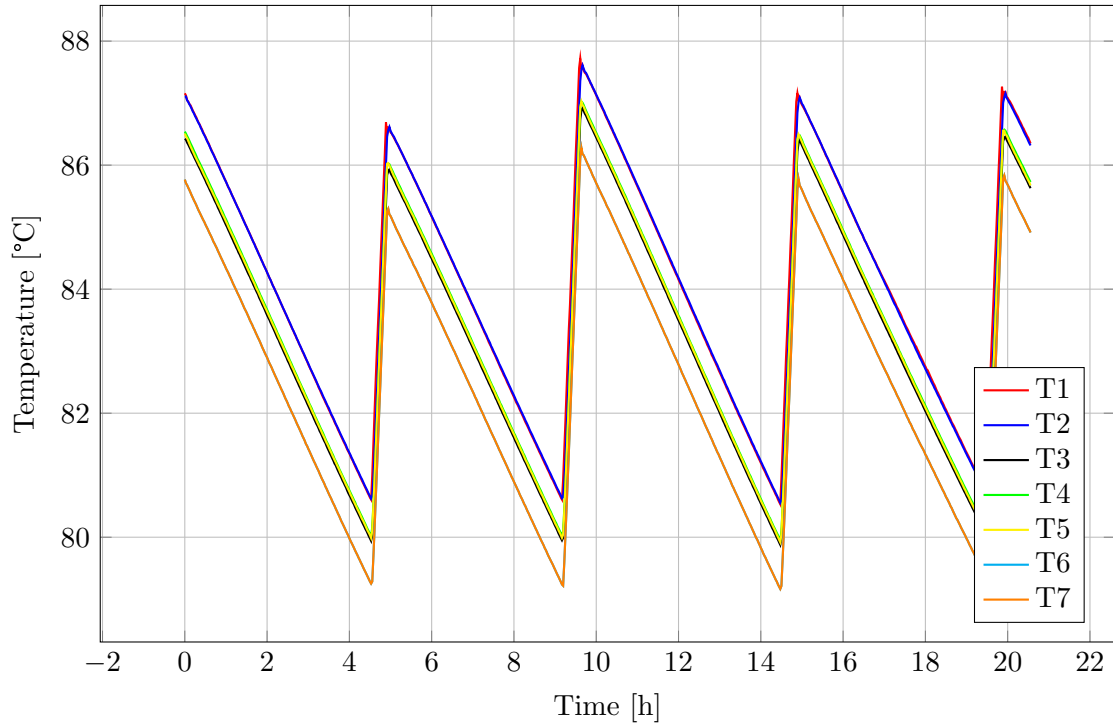


FIGURE A.11: Temperature cycling during standing horizontal operation.

A.5.2 Vertical Test

Similar to the horizontal test above, Figure A.12 shows the water temperature during standing operation, but in a vertical orientation. In this configuration the majority of the water within the tank was at a higher temperature level than in the horizontal configuration. The water in the upper portion of the tank cooled faster, probably due to heat loss through the connected outlet pipes.

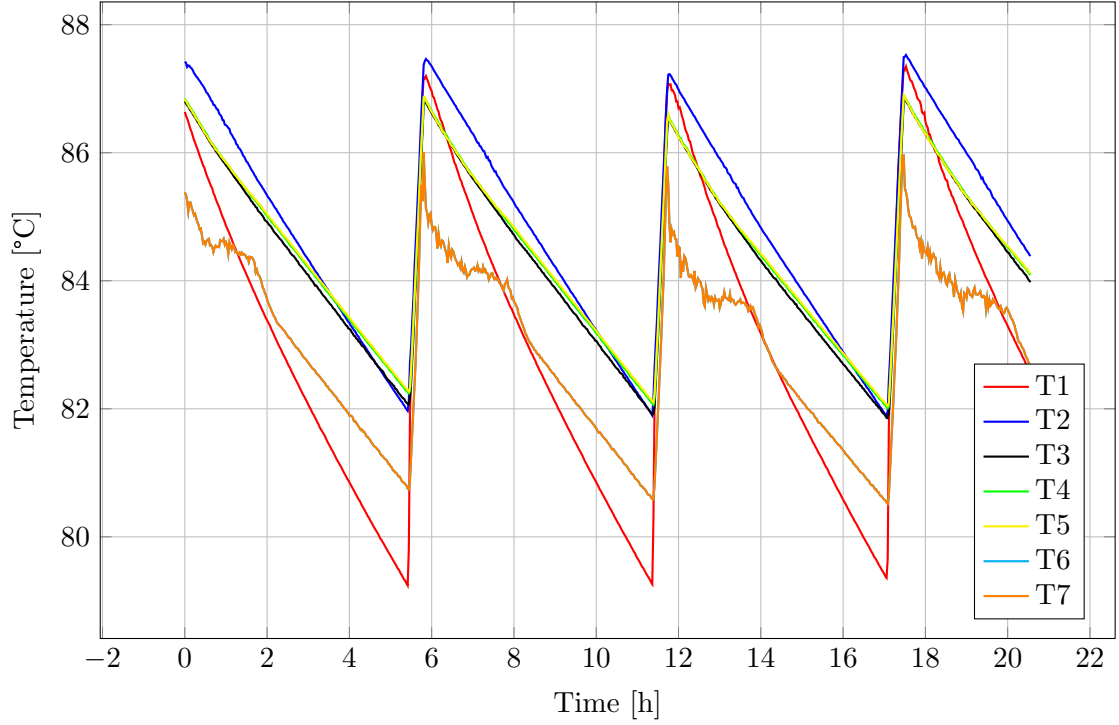


FIGURE A.12: Temperature cycling during standing vertical operation.

A.5.3 Draw-off Test

The Figure A.13 below shows the temperatures measured throughout a vertical tank during a draw off event. Water was allowed to flow out of the tank at a constant rate, until approximately half of the water was used. Thermal stratification can be seen during the draw off and during the temperature recovery. Figure A.14 shows a heat map representation of the same draw off test and shows more clearly how the temperature changed at different heights (thermal stratification) within the tank.

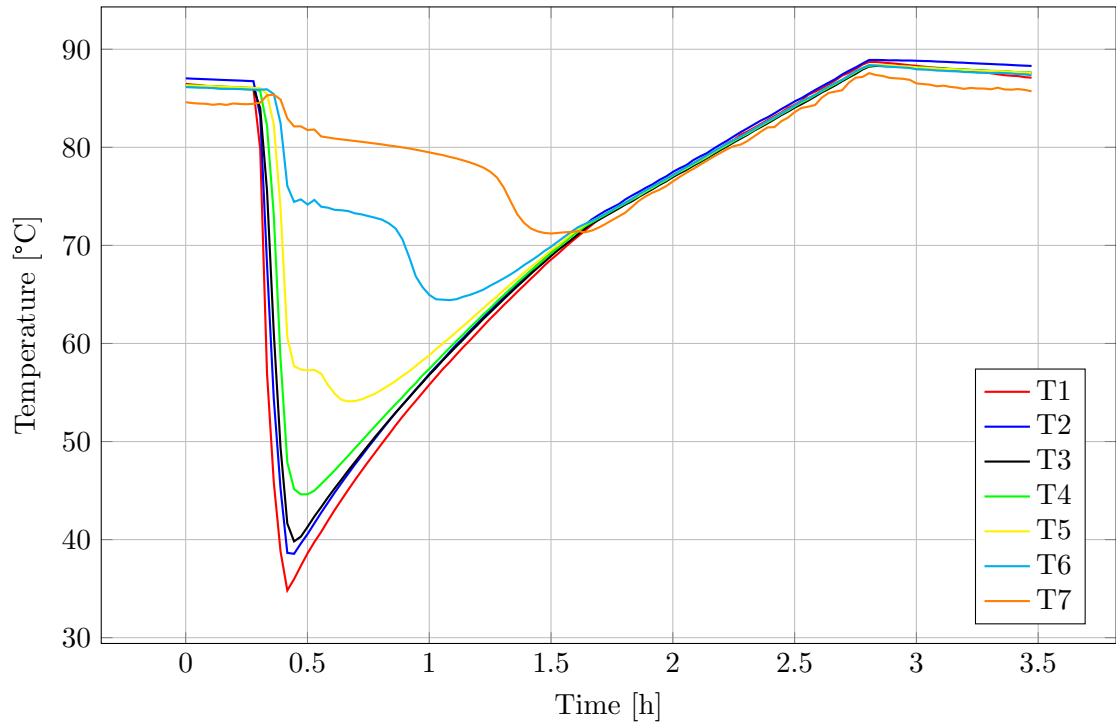


FIGURE A.13: Temperature profile during water draw-off.

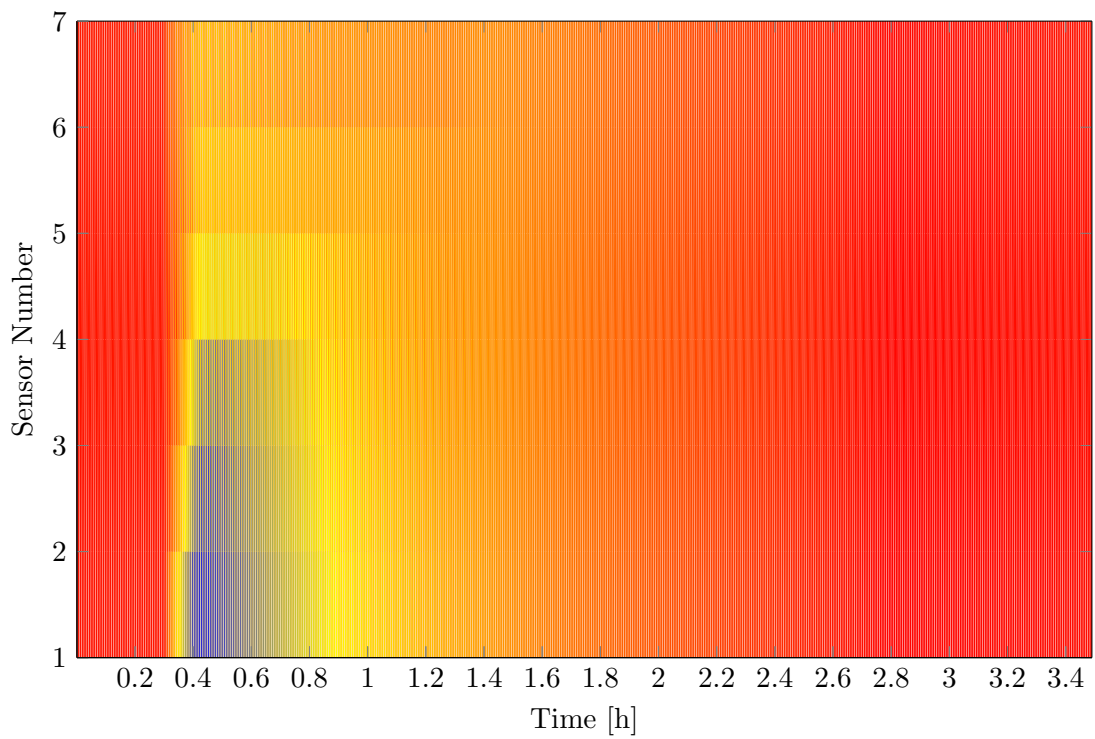


FIGURE A.14: Alternate visualisation of water temperature during draw-off.

A.6 Frequency Measurement

The acquisition of frequency data for the research done above was made possible with a power measurement board designed and built at the University of the Witwatersrand.

A.6.1 Power Measurement Hardware

The physical power board allows for load measurement through a voltage and current measurement. Beyond this basic power determination, it can also measure reactive power and frequency. As the data is measured, it is serially read by a connected FRDM Freescale prototyping board which can be used to post-scale data as a form of calibration. The Figures below show both the power board and the connected FRDM microcontroller.

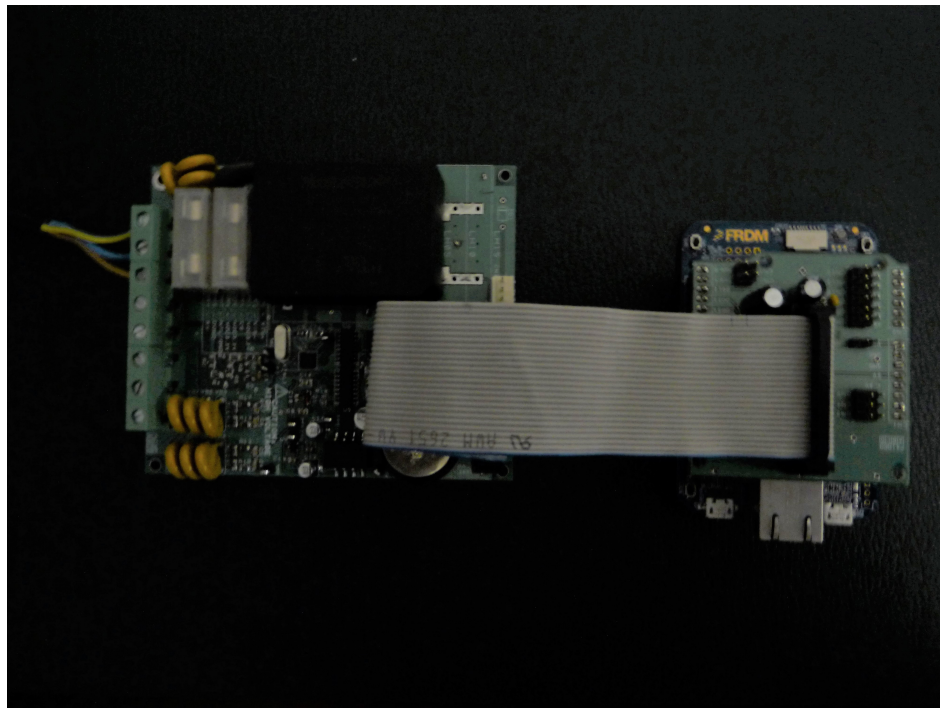


FIGURE A.15: Power board with connected FRDM Freescale.

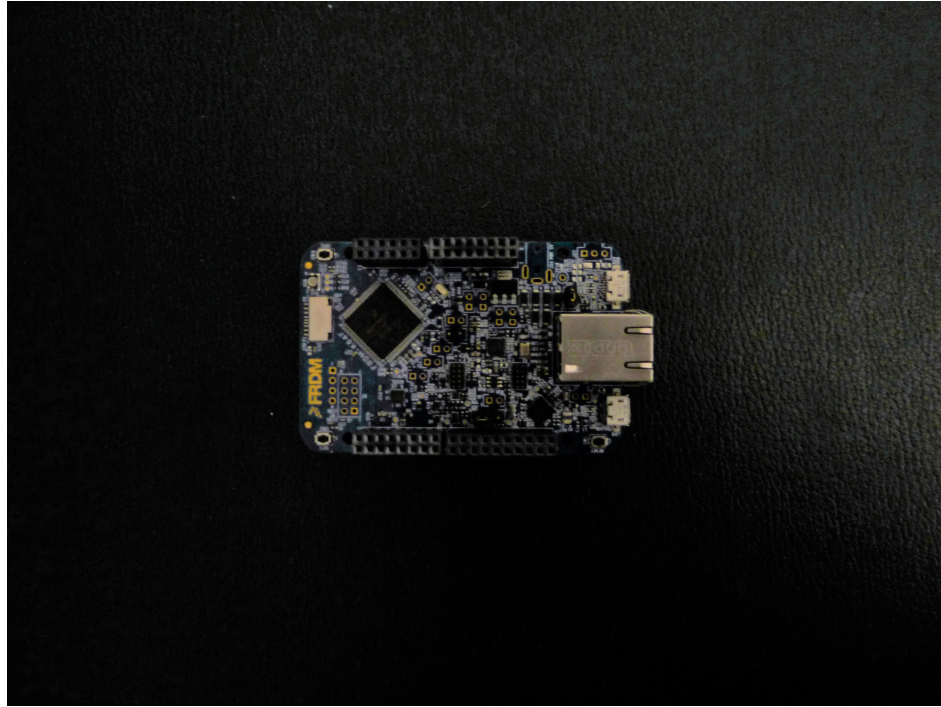


FIGURE A.16: FRDM Freescale prototyping board.

A.6.2 Software Data Manipulation

The FRDM Freescale is connected through a COM port to a computer and transmits per-second data in a continuous, live stream. The program pUTTY was used to save the frequency data sent from the FRDM board as a text file. Post processing algorithms then converted the data into a CSV format with the correct significant numbers.

A.7 Conclusion

This Appendix has focused on presenting the various physical experimentation and measurements performed for the thesis presented. A test bed allowed for water heaters in various orientations to be tested while measuring water temperature, power consumption and water usage. The grid frequency was recorded with a dedicated power board that was designed to measure the power consumption of an individual load.

Appendix B

Contextually Comparing Cooling and Heating Appliances

B.1 Introduction

The viability of thermal appliances as passive energy stores differs primarily on how dispatchable or how deferrable the appliance's load is. Dispatchability is the amount of power the load draws from the grid when turned on and deferrability can be understood as how much or how long the appliance can be used without consuming energy. This Appendix discusses how these aspects vary between typical heating and cooling appliances.

B.2 Viable Thermal Appliances

There is one main requirement for any thermal appliance to be considered viable for use as an energy store: the service it delivers must not be impacted directly by whether or not the appliance is on (actively drawing power). For example a stove or oven is not a suitable energy store - it must be on, consuming power, to provide the exact heat that users require. Appliances with insulation and fluctuating temperatures serve as better energy stores because users receive variable temperatures during normal operation (and with substantial insulation that usable range can be maintained for extended time periods). Domestic water heaters and refrigerators operate in this manner: throughout a day users receive suitably hot water and cold food despite the fact that both types of appliances cycle on and off (often independently of usage) and vary within a range of temperatures.

With this in mind, the following sections focus specifically on comparing the aspects that make thermal appliances viable as energy stores.

B.3 Load Size and Dispatchability

Water heaters in South Africa typically vary between 1 kW and 4 kW of power consumption (manufacturers tend to only produce 1, 1.5, 2, 3 and 4 kiloWatt elements) which makes it simple to generalise the typical water heater load. This variation in consumption usually corresponds to differences in the volume of the tank itself. The fact that the element of a water heater is resistive, simplifies its power consumption to be purely real.

In contrast, the power consumption of a refrigerator or a freezer is not purely real as motors are used to provide the compression. Next, there is notable variation in the power consumption between cooling appliances, due to the push towards efficiency. This means the load consumption for these appliances cannot be generalised simplistically. While a large portion of the available fridges and freezers consume around 0.5 kW, their average consumption will continue to decrease as efficiency improves.

In terms of the power dispatchability, it is immediately clear that a typical water heater can add substantially more load to the grid than a refrigerator. Looking at how long the load can remain on for, impacts the amount of energy that can be dispatched. This maximum time is related to the volume being affected because larger volumes require more time to reach the desired temperature, although higher powered devices do counteract this. The temperature bounds of the appliance also impact the maximum on time and are discussed further below.

B.4 Temperature Bounds and Insulation

Both of the types of appliances mentioned above operate in a cyclical manner, keeping their temperatures within an upper and lower bound. Typically this band of operation is small in order to ensure minimal deviance from the desired set point, but it is possible to widen the band and still have the appliance meet requirements. The benefit of having a large temperature band is that it takes a longer amount of time for the minimum or maximum allowed temperature to be reached, which increases both the dispatchable energy and deferrable energy.

With a water heater, the thermostat usually keeps the internal water temperature within 5 °C of the set point, which is typically set around 70 °C. It is however possible to extend

the operation bound down to 50 °C and up to 90 °C. Below 50 °C there is the risk of bacteria developing in the water system pipes, and above 90 °C the containing tank can be damaged.

The bands of a refrigerator or freezer are more restricted: food stored in a freezer will defrost approaching 0 °C and be damaged below −20 °C; similarly in a fridge, food will freeze below zero and will spoil faster above 5 °C.

When looking at the deferability of these appliances, insulation plays a large role in conjunction with the size of the temperature band. Improving the performance of the insulation improves the deferability as it increases the time it takes the temperature to move between the bounds.

Once again we see that domestic water heaters are potentially better suited to be used as deferrable loads due to their larger acceptable temperature band, as well as the fact that they can be insulated more simply than cooling appliances.

B.5 Non-Domestic Appliances

The conclusion that water heaters are better as deferrable and dispatchable loads is reasonable for the domestic case. However; non-domestic thermal appliances tend to be larger both in size and in power consumption. Buildings often require large spaces to be heated or cooled to provide employee comfort. These HVAC systems have some potential to be used as energy stores, but it is likely that fluctuations in ambient room temperature will be more disrupting to users than fluctuations in other thermal appliances.

Stores that sell fresh produce require large refrigerators and freezers to prevent the decay of perishable items. The core reason that cooling appliances were not considered feasible energy stores is their limited size in a domestic setting. Commercial cooling devices could potentially be utilised, as their greater size make them more dispatchable and deferrable.

B.6 Conclusion

This Appendix looks at the various aspects of thermal appliances that make them suitable as passive energy stores. A focused discussion about domestic appliances concludes that water heaters are more suitable than cooling devices such as freezers and refrigerators, although larger commercial coolers are potentially viable.

Appendix C

Excerpts of Simulation Code

C.1 Introduction

The Appendix below contains sections of the code utilised within simulations run for the dissertation presented above. The purpose of the simulations was to determine the feasibility of autonomous water heater control, based both on the grid frequency and the internal water temperature. In the sections below pertinent code segments are presented and their operation is discussed.

C.2 Water Heater Operation

The class variables of the water heater describe the characteristics of the heater.

```
public class WaterHeater {  
    double volume; //Volume of the tank in litres  
    double temperature; //Average internal water temperature at any given point  
    double radiation; //Convection coefficient impacting cooling time  
    double power; //Power rating of element in kW  
    double ambientTemp; //Temperature of surrounding air  
    int state; //1 if the element is on, 0 if off  
}
```

The advanceTemperature function adjusts the internal water temperature based on whether or not the element is on or off. In the particular case of the code below, this is indicating the temperature change after one second.

```
public void advanceTemperature(){
```

```

double temp = 0; //Placeholder variable
if (this.state == 1){ //Check if the element is on
    temp = temperature+(power)/(volume*4.184); //Increase the temperature
    based on the power of the element and volume of water
}
else
if(this.state == 0){ //Check if the element is off
    temp = ambientTemp +
    (temperature-ambientTemp)*(Math.exp(-radiation)); //Decrease the
    temperature based on ambient temperature and radiation coeff
}
this.setTemperature(temp); //Set the internal temperature to the new value
}

```

C.3 Controller Operation

Both the developed controllers utilize the grid frequency and the water temperature in calculating whether to turn the connected heater on or off.

C.3.1 Dimensional Controller

The Dimensional Controller class variables are detailed below. It operates through measurements of the grid frequency and connected water heater water temperature.

```

public class Controller {
    double freqLower; //Minimum permitted frequency
    double freqUpper; //Maximum permitted frequency
    double deadband; //Width of hysteresis deadband
    double tempLower; //Lowest permitted temperature
    double tempUpper; //Highest permitted temperature
    double gridFrequency; //Holding variable for grid frequency
    WaterHeater load; //Connected water heater
}

```

The Control function operates by taking in the measurement of the grid frequency and using that as well as the control parameters to create comparison checks. Those checks firstly turn the heater on or off based on the controller parameters; and then perform safety checks to ensure maximum temperature is not exceeded; and in the case of low frequency the heater turns off regardless of water temperature.

```

public void Control(double frequency){
    this.gridFrequency = frequency; //Set the grid frequency
    double upperScale =
        (((tempUpper-tempLower)/(freqUpper-freqLower))*(gridFrequency-freqLower))+tempLower;
    //Determine the bound above which the heater will turn off
    double lowerScale = (((tempUpper-tempLower)/(freqUpper-freqLower))*
        (gridFrequency-freqLower-deadband))+tempLower;
    //Determine the bound below which the heater will turn on
    if (load.temperature > upperScale){ //If the temperature is higher that the
        upper bound
        load.setState(0); //Turn heater off
    }
    if (load.temperature < lowerScale && gridFrequency < freqUpper &&
        gridFrequency > freqLower+deadband){
        //Check if the temperature is below the lower bound
        load.setState(1); //Turn heater on
    }
    if (load.temperature > tempUpper){ //Check if max temperature is exceeded
        load.setState(0); //Turn heater off
    }
    if (load.temperature < tempUpper-5 && gridFrequency > freqUpper){
        //Check if grid frequency is higher than max and max temperature is not
        reached
        load.setState(1); //Turn heater on
    }
    if (gridFrequency < freqLower){ //Check if frequency is lower than minimum
        load.setState(0); //Turn heater off
    }
    if (gridFrequency > freqLower + deadband && load.temperature < tempLower){
        //Check if temperature is lower than minimum and frequency is not low
        load.setState(1); //Turn heater on
    }
}
}

```

C.3.2 Statistical Controller

The Statistical Controller has class variables as follows. This includes the variables needed to calculate the control and the water heater object that is attached to the controller.

```

public class Controller {
    double freqX; //Maximum allowed frequency deviation

```

```

double alpha; //Alpha value, typically corresponds to the heater duty cycle
double tempLower; //Minimum permitted temperature to ensure service delivery
double tempUpper; //Maximum permitted temperature to prevent damage
WaterHeater load; //Water heater being controlled
}

```

Similar to the Dimensional Controller above, the Control function takes in the grid frequency and uses both that and the water temperature of the connected water heater to generate a probability for the heater to turn on. This value is then compared to a randomly generated number and (based on the outcome) the heater state is set on or off. The Statistical Controller also includes safety checks for high temperature and for low frequency events.

```

public void Control(double frequency){
    double freq = frequency-50; //Find the frequency deviation
    double scale = (2*(this.load.getTemperature()-this.getTempLower()))/
    (this.getTempUpper()-this.getTempLower()); //Determine the scaling factor
    for biased control

    double M = (this.alpha)/(this.freqX); //Gradient of the statistical control
    double prob = ((M*freq)+this.alpha); //Offset of the statistical control

    double rand = Math.random()*scale; //Generate a random number, scale by
    biased control
    if((rand*100)<=prob){ //Check if element must turn on based on frequency
    and temperature
    this.load.setState(1);
    }
    if((rand*100)>prob){ //Check if element must turn off based on frequency
    and temperature
    this.load.setState(0); }
    if(this.load.getTemperature()>this.getTempUpper()){ //Check if maximum
    temperature is exceeded
    this.load.setState(0);
    }
    if(freq<((-1.0)*freqX)){ //Check if minimum frequency is reached
    this.load.setState(0);
    }
}
}

```

C.4 The Grid

As above, the Grid class variables describe the parameters of the grid, dictating its operation.

```
public class Grid {
    double frequency; //The grid frequency at any given point
    double sensitivity; //The sensitivity of the grid
    double powerConsumption; //The consumption of the heaters on the grid
    double baseLoad; //Base load, kW replaced by controlled loads
    int time; //Incrementing time variable
    ArrayList<Controller> loads = new ArrayList<Controller>(); //Expandable
        list of controllers on the grid
}
```

The advanceState function runs through all controllers and water heaters connected to the grid. This allows them to perform operations individually, given the current state of the grid. During this process the amount of power added or removed from the grid is kept track of and used to determine the change of frequency.

```
public double[] advanceState(){
    this.time++; //Increment the simulation time
    int pre; //Holding variable for previous state of current heater
    double[] temp = new double[this.loads.size()]; //List used to store all
        water temperatures

    for (int n=1;n<loads.size();n++){ //Loops through all loads on grid
        pre=0; //Defaults the water heater state as 'off'
        if(loads.get(n).getLoad().getState()==1){
            pre = 1; //Stores the state to 'on' if it is
        }
        loads.get(n).control(this.getFrequency()); //Apply the control function
        to the current load
        if(loads.get(n).getLoad().getState()==1 && pre == 0){ //Check if the
            heater has turned on due to control

            this.setPowerConsumption(this.getPowerConsumption()+loads.get(n).getLoad().getPower());
                //Increase the grid power consumption by the power of the current
            heater
        }
        if(loads.get(n).getLoad().getState()==0 && pre == 1){ //Check if the
            heater has turned off due to control

```

```

    this.setPowerConsumption(this.getPowerConsumption()-loads.get(n).getLoad().getPower());
        //Decrease the grid power consumption by the power of the current
    heater
    }
    if(loads.get(n).getLoad().getState()== pre){ //Check if the heater has
    not changed state
        this.setPowerConsumption(this.getPowerConsumption());
        //Make no change to the current power consumption
    }
    loads.get(n).load.advanceTemperature(); //Advance the temperature of the
    water heater
    temp[n] = loads.get(n).load.getTemperature(); //Store the new temperature
}
double deltaFreq =
    (((this.getPowerConsumption()-this.getBaseLoad())*this.getPowerCapacity()));
//Calculate the change in frequency due to the difference from the base load

this.setFrequency(this.getFrequency()-deltaFreq);
//Set the grid frequency to the adjusted value

return temp; //Return the store water temperatures
}

```

C.5 Main Code

The Main code contains the initialisation of the various objects within the simulation, as well the reading and writing of data to and from text files. A rundown for a typical main code is presented below.

```

public static void main(String[] args) throws IOException,
    FileNotFoundException {
    System.out.println("Begin");
    Writer tester = new Writer("Results.txt", true);
    tester.clearFile();
    //Create and clear text file for results

    Scanner read = new Scanner(new File("freq.txt"));
    read.useDelimiter(",");
    String holder;
    //Create a scanner to read pre-measured frequency values

```

```

WaterHeater one = new WaterHeater(100, 70, 0.0000035, 2, 25, 0);
//Creation of a water heater with standard variables
Controller cont = new Controller(0.4, 3.2, 55, 85, 50, one);
//Creation of a statistical controller for the above water heater

Grid grid = new Grid(50, 0.003, 128, 0, 0, cont);
//Creation of the grid with the above controller attached
for(int num = 0; num<1000;num++){
    grid.addLoad(new Controller(0.4, 3.2, 55, 85, 50, new
        WaterHeater(100, (Math.random()*10)+65, 0, 0.0000035, 2, 25, 0)));
    //Add 1000 identical controllers and water heaters to the grid.
    //Water heater initial temperatures vary randomly between 65 and 75
    degrees
}
System.out.println("Initialised");
holder = read.next();
grid.setFrequency(Double.parseDouble(holder)); //Set the frequency as per
the text file
(int i = 0; i < 40000; i++) { //Loop through 40000 cycles
    double[] temp = new double[grid.loads.size()];
    System.arraycopy(grid.advanceState(), 0, temp, 0, grid.loads.size());
    //Create holding array and use it to store all the temperatures from the
    //heaters as they advance state
    tester.writeToFile(i+" "+grid.getPowerConsumption()+" "+
        (grid.getBaseLoad())+ " " + (grid.getFrequency()-50)+" "+(
        Double.parseDouble(holder)-50)+" ");
    //Write all changing grid variables to the text file
    for (int j = 0; j < temp.length; j++) { //Loop through all recorded
    temperatures

    tester.writeToFile(String.valueOf(Math.round(temp[j]*100.0)/(100.0))+ " ");
        //Write the temperatures to the test file
    }
    tester.writeToFile("\r\n");
    holder = read.next();
    grid.setFrequency((grid.getFrequency()+Double.parseDouble(holder))/2);
    //Set the grid frequency to an average of the pre-measured and result of
    the control
    }
System.out.println("Complete");
read.close();
}

```

C.6 Conclusion

This Appendix has presented various elements of the simulation code used for the presented thesis. The important classes were described and notable computations were shown. Comments detailed within the code aim to provide further insight into the operation of the simulations.

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