TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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AGGREGATED ELECTRIC SPACE HEATER LOAD MODEL FOR POWER SYSTEM FREQUENCY CONTROL ANALYSIS

Master of Science thesis

Examiner: Prof. Sami Repo
Examiner and topic approved by the Faculty Council of the Faculty of Computing and Electrical Engineering
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ABSTRACT

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Maintaining constant system frequency in a power system is vital for its operation. The power system's frequency is kept at acceptable levels by maintaining a power balance between the produced and consumed electric power in the power system. Traditionally, the power system's frequency control is done by controlling the supply side output power and matching it with the demand side consumption. However, the power balance could also be maintained by controlling the demand side loads. Demand response seeks to improve this utilization of demand side loads in frequency control.

Demand response includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand or total electricity consumption. For the transmission system operators, that are responsible for frequency control, demand response offers potential solutions to some of the problems that the Nordic power system operation sees today. As the use of intermittent power production (wind power, solar power) is increasing, the maintenance of the power balance becomes more difficult. Demand side load control can be a potential solution in decreasing these negative effects of renewable energy production for frequency control. Additionally, load control as a form of frequency reserve has a high economic potential in the frequency reserve markets that are currently dominated by the hydropower. Load control can be seen as an opener to improve the frequency reserve market competition, if the technology can be realized for frequency control.

From the various electric load types that are suitable for load control, different electric heating loads offer a large control potential in Finland during the heating season. In this thesis is presented an aggregated model of electric, thermostat-controlled space heater loads, which can be used to analyze the compatibility of this type of electrical load for frequency control. The model is designed to represent the characteristics of Finland regarding the environment, power system operation and residential building related parameters. With this model, simulations regarding the uncertainties, load forecasting and effects of frequency control action were carried out. From these simulations it could be concluded, that this type of electrical load can be utilized for load control, if the load population is large enough and the control action is not too long. The methodology used in this thesis can also be used to expand the model on other similar type electrical loads.

TIIVISTELMÄ

ANTTI LEHTONEN: Aggregoitu sähkölämmityskuormamalli sähköverkon taajuussäädön analyysiin
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Avainsanat: aggregoitu malli, kysynnänjousto, taajuuden säätö, taajuusreservi

Sähköjärjestelmän toimivuuden kannalta on oleellista, että sen taajuus pysyy lähellä nimellisarvoa. Sähköverkon taajuus pidetään halutussa arvossa ylläpitämällä tehotasapainoa, missä sähköverkon tuotettu ja kulutettu teho ovat yhtä suuret. Perinteisesti tehotasapainoa on ylläpidetty säätämällä tuotantopuolen tehoa vastaamaan kulutustehoa. Tehotasapainoa voitaisiin kuitenkin yhtä hyvin ylläpitää myös säätämällä kulutuspuolen kuormitusta. Tätä kulutuspuolen kuormanohjausta pyritään lisäämään kysynnänjouston avulla.

Kysynnänjoustoon sisältyvät kaikki tarkoitukselliset sähkön loppukäyttäjän tekemät muutokset sähkönkulutukseensa, joilla on tarkoitus muuttaa sähkönkäytön ajoitusta, huipputehoa tai kokonaiskulutusta. Kantaverkkoyhtiöille, joiden vastuulla on sähköverkon taajuuden säätäminen, kysynnänjousto tarjoaa potentiaalisia ratkaisuja ongelmiin, joita Pohjoismaiden yhteiskäyttöverkko tällä hetkellä kokee. Kun epäsäännöllisesti tehoa tuottavien tuotantolaitosten (tuulivoima, aurinkovoima) käyttö lisääntyy, tehotasapainon ylläpito hankaloituu. Tätä negatiivista ilmiötä voidaan mahdollisesti lieventää kuormanohjauksella, joka tarjoaa monipuolisuutta ja joustavuutta taajuuden säätöön. Kuormanohjauksella on lisäksi korkea taloudellinen potentiaali taajuuden reservimarkkinoilla, joita tällä hetkellä vesivoima vahvasti hallitsee. Kuormanohjaus voisi lisätä tervettä kilpailua reservimarkkinoille, mikäli kuormanohjausteknologia soveltuu käytettäväksi taajuuden säätöön.

Erilaisista sähkökuormista, jotka soveltuvat kuormanohjaukseen, erilaiset sähkölämmityskuormat muodostavat ison säätöpotentiaalin Suomessa lämmityskaudella. Tässä työssä on tuotettu aggregoitu malli termostaattiohjatusta rakennusten sähkölämmityksestä, jota voidaan käyttää arvioimaan sähkölämmityskuorman soveltuvuutta taajuuden säätöön. Malli on suunniteltu kuvaamaan sähkölämmitystä Suomessa, ottaen huomioon eri Suomen ympäristöön, rakennuksiin ja sähköjärjestelmän toimintaan liittyvät asiat. Tällä mallilla voitiin myös tehdä simulointeja liittyen kuormapopulaation epävarmuustekijöihin, kuormitettavuuden ennustamiseen sekä kuormien käyttäytymiseen kuormanohjauksessa. Simulointien tuloksista voitiin päätellä, että sähkölämmityskuormat soveltuvat käytettäväksi taajuuden säätöön, jos kuormapopulaatio on riittävän iso sekä ohjaustoiminto ei ole liian pitkä. Tässä työssä esiteltyä mallinnustapaa voidaan myös käyttää laajentamaan mallia käsittämään muitakin saman tyyppisiä sähkökuormia.

PREFACE

This master's thesis was done for the department of electrical energy engineering at Tampere University of Technology. The supervisor and the examiner for this thesis was professor Sami Repo. I want to thank Sami for providing me with an interesting thesis topic as well as giving me guidance and feedback during the making of it.

This master's thesis concludes my studies at the Tampere University of Technology. The graduation from this university was the hardest task I have personally ever faced but with long-term determination, I have finally achieved my master's degree.

Tampere, 23.5.2017

Antti Lehtonen

CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

AC	Alternating Current
AGC	Automatic Generator Control
AMR	Automatic Meter Reading
CIGRE	International Council on Large Electric Systems
DNO	Distribution Network Operator
DR	Demand Response
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal operation
FRR-A	Frequency Restoration Reserve, Automatic
FRR-M	Frequency Restoration Reserve, Manual
IEEE	Institute of Electrical and Electronics Engineers
RGN	Regional Group Nordic
RR	Replacement Reserve
TSO	Transmission System Operator

A_i	area of part i
C	heat capacity
c_{pi}	specific heat capacity of air
f	system frequency
f_N	nominal system frequency
H	heat transfer coefficient
$H_{coldbridge}$	cold bridge heat transfer coefficient
H_{cond}	conduction heat transfer coefficient
H_{door}	door heat transfer coefficient
H_{floor}	floor heat transfer coefficient
$H_{leakage}$	air leakage heat transfer coefficient
H_{part}	heat transfer coefficient of a specific part
H_{roof}	roof heat transfer coefficient
H_{vent}	ventilation heat transfer coefficient
H_{wall}	wall heat transfer coefficient
H_{window}	window heat transfer coefficient
J	inertia of a rotating mass
l_k	length of the line like cold bridge
P_{heat}	rate of building heat gain
P_{loss}	rate of building heat loss
P_{misc}	heating power from other heating sources
P_N	nominal turbine output power
P_t	turbine output power
$Q_{heating,spaces,net}$	net heating energy need for space heating of a building
Q_{space}	heating energy need for space heating of a building
$Q_{in.heat}$	other heat loads that are used for space heating

q_{lp}	air leakage stream, ventilation removal air stream
r	positive constant
s	droop
t	time
τ	building time constant
T	temperature
$T(0)$	initial temperature of a body
T_{env}	temperature surrounding a body
T_{hlim}	thermostat higher limit
T_i	indoor temperature
T_{iref}	indoor temperature reference
T_{llim}	thermostat lower limit
T_o	outdoor temperature
T_{oref}	outdoor temperature reference
T_{set}	thermostat set value
U_i	thermal transmittance of part i
W_k	kinetic energy
ω	angular speed of a rotating mass
Ψ_k	additional conductance of a line like cold bridge
ρ_i	air density

1. INTRODUCTION

In an alternating current (AC) power system, maintaining constant system frequency is vital for its operation. As the system frequency is directly proportional to the rotational speed of the large synchronous generator's that are used for the power system's power production, a power balance between the produced and consumed power has to be maintained. As the power system's power production and consumption changes constantly, continuous monitoring and control actions need to be taken to maintain proper system frequency. In today's power system, the power balance is primarily maintained on the supply side by controlling the synchronous generator's output power production to match the current power consumption levels. However, the power balance could also be maintained on the supply side by controlling the customer's loads. Demand response seeks to improve this utilization of demand side loads in power system frequency control.

Demand response includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand or total electricity consumption. For the transmission system operators, that are responsible for frequency control, demand response offers potential solutions to some of the problems that the Nordic power system operation sees today. As the use of emission free and renewable energy production, namely wind power and solar power, is increasing in our power system, it has a negative effect on the frequency stability. As the power production of these renewable energy sources is intermittent in nature, it makes the maintenance of power balance more difficult. Demand response can potentially diminish these negative effects by providing a more robust and flexible frequency control options. Additionally, demand response has a lot of economic potential to be used as a part of the frequency control. This is because the competition of frequency reserve markets is currently dominated by hydropower that offers a fast and cheap supply side frequency control reserve. Load control can be seen as an opener to improve the frequency reserve market competition by adding cheap demand side options for frequency control.

Not every electrical load is suitable to be used for load control. In general, the control of the loads should not cause a negative experience for the customer. This means, that the loads that are to be used for load control, should be relatively insensitive to their time of use. From these types of loads, various types of electrical heating loads offer the largest amount of potential capacity for load control during the heating season in Finland. As the heating season in Finland is 9 months of the year, electrical heating loads create a considerable amount of energy consumption during the cold period. In this thesis, the focus of examination is the residential, thermostat-controlled space heater loads. Generally, the use of electrical energy for heating is economically viable in small residential buildings. This is also reflected in residential building heating statistics. Electric space heating is used in about 38 % of all buildings in Finland, but the consumption of electrical energy for heating is only about 20 – 25 % of the total heating energy consumption. This make the electric space heating loads to be high in volume, but low in unit size.

The purpose of this thesis is to study the viability of electric, thermostat-controlled heating loads to be used in load control. The method of research is to develop an aggregated model of the space heater to simulate the behavior of a load control group that consists of thousands of individual loads. The aggregated model uses a reference model as its basis that can be then scaled up to different sizes by using randomly generated parameter values for each individual load. This model is also designed to represent the characteristics of Finland regarding the environment, power system operation and residential building related parameters. When studying the suitability of this type of load to be used for frequency control, the following three main characteristics are considered:

Uncertainty of the power usage of the load control group
For the load control group to be suitable for frequency control, the uncertainties caused by the intermittent power usage of the thermostat-controlled loads needs to be understood.

Load forecasting
The power usage of the electrical space heaters is not constant, as the outdoor temperature has a strong correlation to the usage of heating power. For this type of load to be used for frequency control, it is important to understand how easy it is to predict the power usage pattern of the load.

Behavior of the load control group after the control action
For thermostat-controlled loads, the load control action may cause a lot of unwanted synchronization. In the case of heating loads, this synchronization, also known as cold-load pickup, may cause the power system loading to increase after the load control action. This kind of behavior needs to be known in order to be able to create a properly working frequency reserve using load control.

One important consideration of the load control technology to be used for frequency control is the method of control (e.g. local, centralized) and the actual controller technology (e.g. AMR-meter, HEMS). In this study, these considerations are not taken in to account. Additionally, the model only considers the use of a simple, on/off –type thermostat to be used to control the loads. The methodology used in this study can also be expanded to be utilized for other loads that use a thermostat or similar controller.

This thesis has the following structure: in chapter 2 is introduced the general frequency control theory and in chapter 3 is presented the unique features of the Nordic power system as well as the electricity market. Chapter 4 discusses the potential of demand response for frequency control. In chapter 5, the aggregated model for the electric space heater loads is developed and in chapter 6, simulations regarding the compatibility of the electric space heater loads are done using the aggregated model. In chapter 7, the conclusions of the study are given.

2. FREQUENCY CONTROL THEORY

In this chapter, the theory and application of a power system frequency control is being presented. In the first part, the power system frequency stability and operation of synchronous generators is discussed. In the second part, the different frequency reserves that are used for frequency control in Europe are revised. In the last part, the actual frequency control action that is used to restore frequency stability after a disturbance is being explained.

2.1 Power system stability

A power system is a non-linear and dynamic electric system where the electricity consumption, production and transmission states are constantly changing [3]. This means that in order for the power system to remain in operating equilibrium, constant monitoring and stabilization actions are required. The power system's ability to maintain the operating equilibrium is referred as power system stability. In 2004, the IEEE and CIGRE joint task force proposed the definition for power system stability as the "ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact" [12]. In Figure 2.1 is shown the different phenomena that lead to power system instability, followed by their definitions.

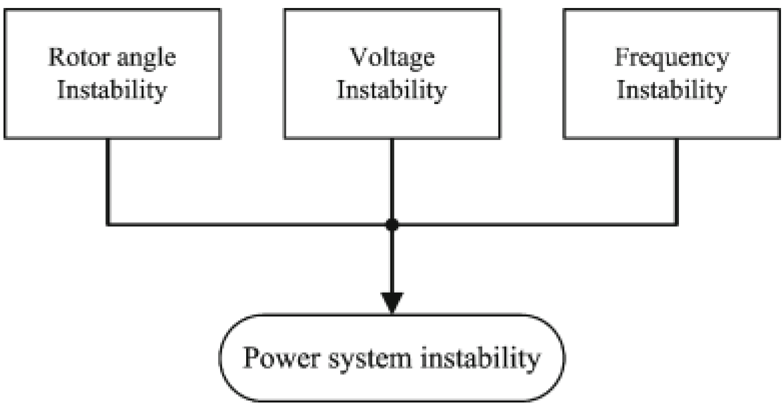

Figure 2.1 *Different phenomena that lead to power system instability [2]*

Rotor angle instability is the inability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance [12].

Voltage instability is the inability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial condition [12].

Frequency instability is the inability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between the generation and load [12].

For a power system to stay operational, all three of the stability criteria need to be satisfied simultaneously at all times. The transmission system operator (TSO) has the responsibility to ensure that the system stays operational with high level of reliability and security. For this, the TSO has to coordinate the instability-preventing processes so that they satisfy the quality requirements set to the power system. To prevent rotor angle instability, the power system needs to have a well-coordinated and fast-acting fault clearing system. Voltage stability is mostly maintained with good reactive power control and frequency stability requires a diverse real power control. In the following chapter, power system frequency stability is explained in more detail. [3]

2.1.1 Frequency stability

Steady frequency is a vital parameter for power system operation. It indicates that the generation and load are in balance in the power system. Furthermore, constant network frequency ensures that the power stations run satisfactorily in parallel, the various electric motors run at the desired speeds and that the correct time is obtained from synchronous clocks [3]. Generator turbines are also designed to operate at the nominal system frequency and if the system frequency decreases significantly, generators have to be disconnected in order to avoid turbine damage. The disconnection of generators due to low system frequency will further decrease the system frequency and, in the worst-case scenario, lead in to a frequency collapse that causes the entire power system to be unable to operate. To prevent frequency instability in a power system, a real power balance needs to be maintained. [3]

As large-scale energy storage used in a power system is not currently practical, the produced and consumed electrical energy in a power system needs to be in balance at all times. If this balance, referred as the power balance, is disturbed, the power system's frequency will change. If the consumption of real power in the power system is greater than the real power produced by the generators, the additional energy needed to balance the system is taken from the kinetic energy of the generator. This slows down the generator and therefore decreases the system frequency. If the production of real power in the generators is greater than real power consumption in the power system, the opposite occurs, and the generator starts to accelerate increasing the system frequency. [3] As the consumption and production of electrical energy of a power system changes during operation constantly, it needs to be possible to control the generation or loading of the system in order to maintain the power balance.

The consumption of electrical energy during normal operation can vary significantly depending on the day of the week or the time of the day. Additionally, different types of disturbances can cause a very fast change in the real power generation if a production unit needs to be disconnected from the power system. In order for the power system to maintain frequency stability, the control of generation or loading need to be able to cover the different time scales where the real power imbalance can occur. This dynamic has led to a solution, where the frequency control is realized by using a combination of control methods that active within seconds, to provide momentary frequency stabilization, to a various systems activating in some minutes, to restore the frequency back to nominal. Furthermore, frequency control consists of hourly (Elbas-market) and daily (Elspot-market) balancing actions done through the electricity markets, which is discussed more in chapter 3.2. Additionally, the planning of power plant maintenance and future investments are part of the long-term power balance maintenance strategy.

2.1.2 Synchronous generators

The frequency of a power system originates from the synchronous generators that are used to produce the large majority of the AC power. As the magnetized rotor of a synchronous machine sweeps past the stator coils, the induced voltage changes direction depending on the relative motion of the magnetic field that passes through it. Essentially, this means that the frequency of the voltage produced by the generator is directly proportional to the speed of its rotor. Therefore, generator speed control can be utilized to control the power system’s frequency. In addition, the synchronous generator’s mechanical properties have effect on the frequency variations.

As synchronous generators used for power generation have massive cylindrical rotators, a large amount of rotational kinetic energy is stored in them. The kinetic energy W_k stored in these rotating masses is defined by Equation (2.1):

$$W_k = \frac{J\omega^2}{2} \tag{2.1}$$

where J is the inertia of the rotating mass and ω is the angular speed of the rotating mass [3]. When the loading changes in a power system and the synchronous generator starts to accelerate or decelerate, the inertia of the rotating mass tries to resist this change of motion. It follows from this physical phenomena that the rate of change of frequency in a power system, caused by a change in the power balance, is dependent of the combined kinetic energy that is stored in all of the power system’s synchronous generators. The kinetic energy of a power system is a critical parameter for the design of frequency control, as the effects of rotational inertia diminish the system's frequency variations before any other type of control has time to react. If, however, the system frequency shifts out of the defined operational limits, the synchronous generators speed control is the first form of frequency stabilization that tries to restore the system frequency back to nominal.

In order to change the rotational speed of a synchronous generator, its real power output needs to be changed. The real power delivered by a generator is controlled by the mechanical power output of a prime mover such as a steam turbine, gas turbine, hydro-turbine or diesel engine. [2] The prime mover controller systems for generators have ranged from old mechanical systems to the utilization of modern digital control. Nevertheless, while the generator speed control have seen technological advancement over the years, the fundamental operation principle this applies. In Figure 2.2 is shown a block diagram of a general synchronous generator speed control system using two control loops.

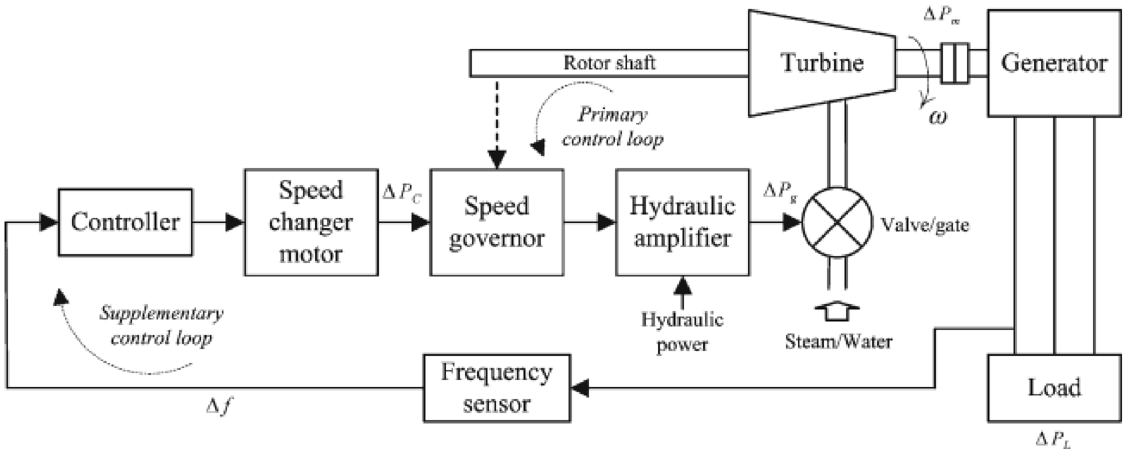

Figure 2.2 *Block diagram of a synchronous generator speed control system [2]*

In the generator speed control system of Figure 2.2, the speed governor senses the change in speed (frequency) via the primary and supplementary control loops. The primary control loop measures the change in the speed of the generator rotor locally. The primary control loop operates as a proportional controller and it is not able to restore the power system's frequency to its nominal value, as there will always be a steady-state error in frequency after the control action. To remove the steady-state error in the frequency, a supplementary control loop is used. The secondary control loop, that is used to restore the system frequency to nominal, can be a manual operation (like in the Nordic power system) or an automated operation (like in Continental Europe's power system) [3]. The coordination of generator speed control also becomes more challenging in real-life power systems, where there are multiple generators controlling the system frequency. In these multi-generator systems, droop needs to be applied.

As frequency is a quantity that is shared within the entire power system, the synchronous generators' speed controllers will react to frequency deviations simultaneously regardless of the generators' physical locations. This means that if no additional action is taken, the frequency control action would divide very unevenly between the power system's generators operating in parallel and the generators would compete against each other for the control. To counter this, droop (sometimes referred as *statism* or just *speed-droop*) is used across all the different generators in the power system. The droop of a generator expresses how sensitive it is to frequency deviations. Droop is defined by Equation (2.2):

$$s = \frac{\Delta f / f_N}{\Delta P_t / P_R} \cdot 100\ \% \tag{2.2}$$

where ΔP_t is the change in the turbines output power, P_R is the nominal output power of the turbine, Δf is the change in system frequency and f_N is the nominal system frequency [3]. From Equation (2.2) it can determined, that if a generator has a droop of 0 %, the output power of a turbine will not change when the system frequency changes. On the other hand, a generator with a droop of 5 %, will change its turbines output power from zero to nominal if the system frequency decreases by 5 %. In a real-life power system different generators have different values of droop. This means that when the system frequency decreases, some generators change their turbines output power more than others do.

In practice, generators can only increase their turbine output power to its nominal value. This means that in order for a generator to be able to increase the system frequency, it has to be run at sub-nominal power. The amount of power capacity, meaning the amount of power a generator's output can be increased, that is available in the power system is referred as a spinning reserve [3]. While the spinning reserve is a fast-acting reserve for frequency control, it can only be used to stabilize frequency momentarily before it is out of capacity. Therefore, maintaining the frequency stability of a power system requires a more diversified combination of frequency reserves that will be discussed in the next section.

2.2 Frequency reserves

Frequency reserves are used to maintain system frequency at nominal level when the power balance of a power system is being disturbed. Frequency reserves consist of processes that can alter the generation or loading of a power system. The frequency reserves used in Europe are defined by the European Network of Transmission System

Operators for Electricity (ENTSO-E). As the frequency of a power system is only shared within the same synchronously interconnected power system, Europe has further been divided in to five different regional groups [6]. In Figure 2.3 is shown the regional groups based on the synchronous areas in Europe.

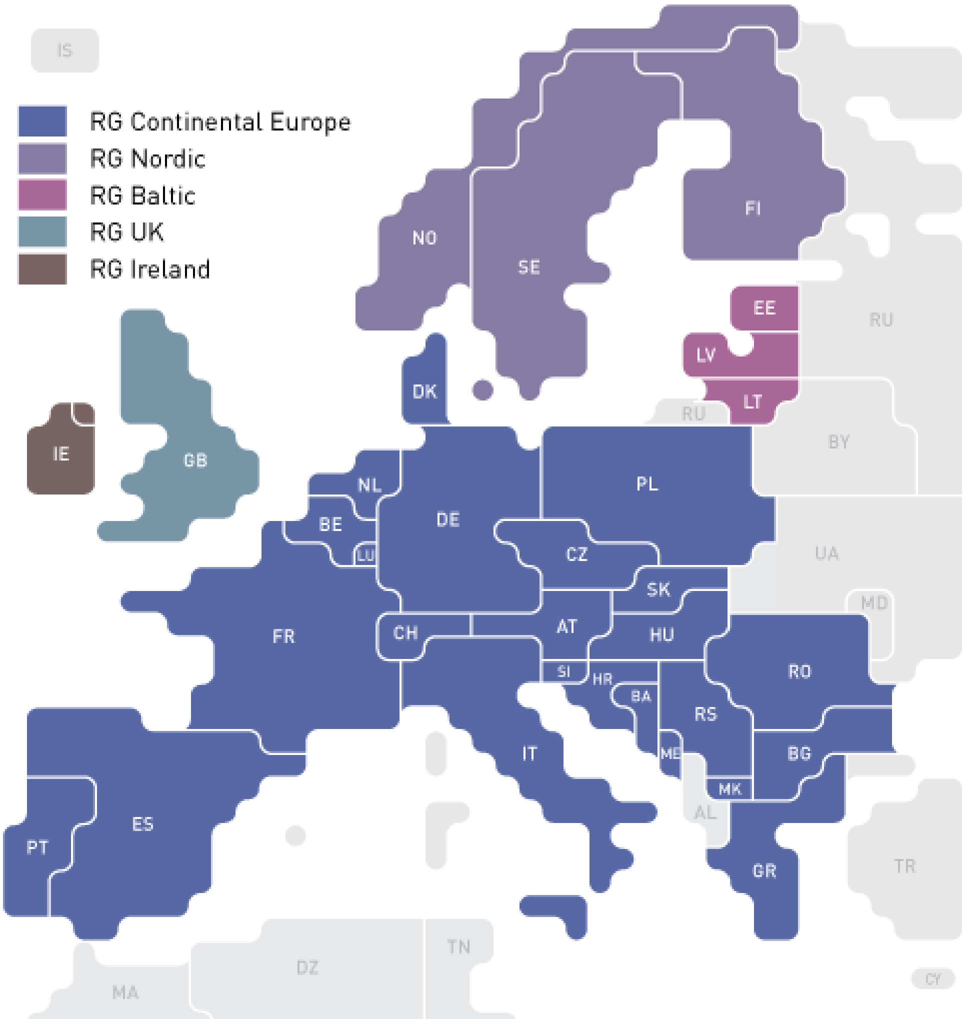

Figure 2.3 *Regional groups based on the synchronous areas in Europe [6]*

These regional groups will continue the system operation activities of former TSO associations in Europe, addressing technical and operational aspects specific to their synchronously interconnected system operation. The current and former TSO associations are as follows:

- Continental Europe – former UCTE
- Nordic – former NORDEL
- Baltic – former BALTSO
- UK – former UKTSOA
- Ireland – former ATSOI

While the Europe has been divided in to regional groups, the definitions for frequency reserves have been generalized for all regions. It is up to the regional groups to define the detailed use of frequency reserves in their specific synchronously interconnected system to satisfy the requirements for frequency quality [6]. As the balance between the generation and load can shift in seconds during a disturbance, or see a slower change during the day, the frequency reserves need to be able to cover the different time scales that the imbalances can take place in. Therefore, the frequency reserves are divided in to different processes based on their activation speed.

ENTSO-E has defined the used frequency reserve processes as the frequency containment reserves, frequency restoration reserves and replacement reserves [6]. In Figure 2.4 is shown the different frequency reserve products and their general activation times, followed by their definitions.

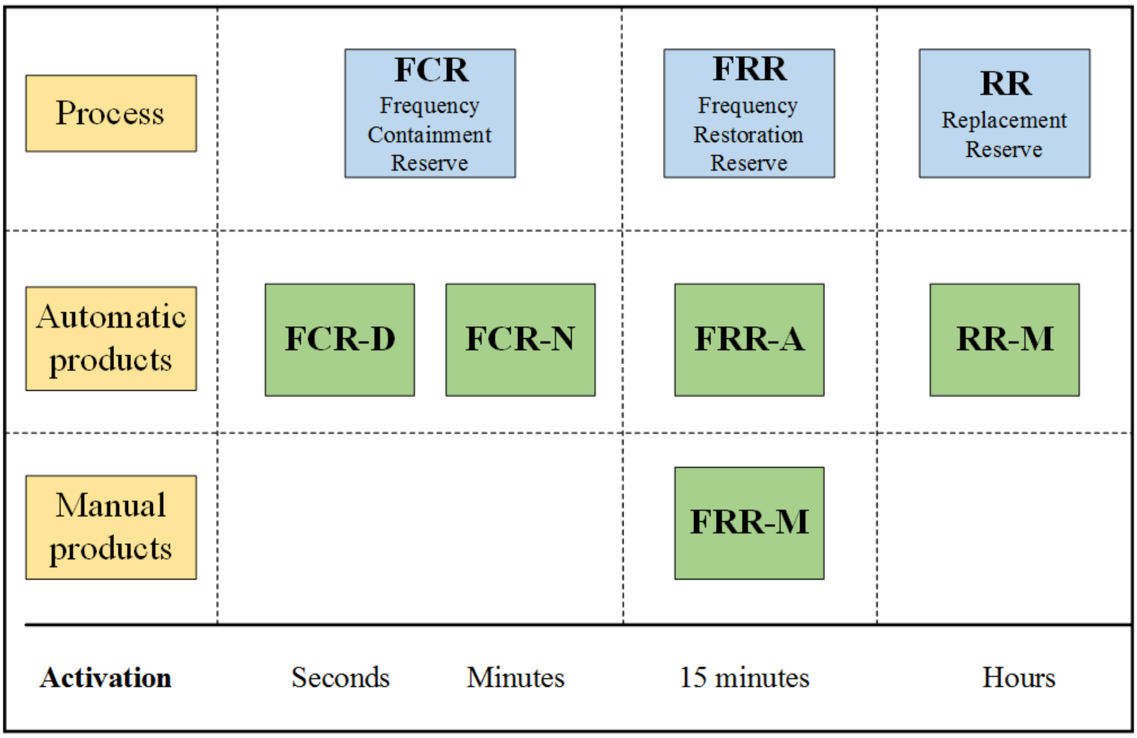

Figure 2.4 *Different frequency reserves used in frequency control in Europe. Figure is adapted from [5] and [7]*

Frequency containment reserve (FCR) aims to increase the operational reliability of the synchronous area by stabilizing the system frequency in the time-frame of seconds at an acceptable stationary value after a disturbance or incident; it does not restore the system frequency to the set point. Frequency containment depends on reserve providing units (e.g. generating units, controllable load resources and HVDC cables) made available to the system in combination with the physical stabilizing effect from all connected rotating machines. As a generation resource it is a fast-acting, automatic and decentralized function, e.g. of the turbine speed governor, that adjusts the power output in the case of system frequency deviation. Frequency containment reserves are activated locally and automatically at the site of the reserve-providing unit, independently from the activation of other types of reserves. Furthermore, the products of FCR are divided in to disturbance reserves (FCR-D) and normal operation reserves (FCR-N) depending on their function. [5]

Frequency restoration reserve (FRR) aims to restore the system frequency in the time frame defined within the synchronous area by releasing system wide activated frequency containment reserves. Frequency restoration depends on reserve providing units made available to the TSOs, independent from FCR. Activation of Frequency Restoration Reserve (FRR) modifies the active power set points or adjustments of reserve providing units in the time frame of seconds up to typically 15 minutes after a disturbance. In each control area, FRR are activated centrally at the TSO control center, either automatically (FRR-A) or manually (FRR-M). Frequency restoration must not impair the frequency containment that is operated in the synchronous area in parallel. [5]

Replacement reserves (RR) are needed to prepare for further imbalances in case FCR or FRR has already been activated. The RR activation time and the needed capacity is dependent of the power system's structure and overall frequency control strategy. RRs are activated manually and centrally at the TSO control center in case of observed or expected sustained activation of FRR and in the absence of a market response. TSO can also use RRs to anticipate on expected imbalances. Replacement reserves depend on reserve providing units made available to the TSOs, independently from FCR of FRR. RRs are used to release FCR and FRR or to prevent their activation in normal operation. [5]

Some loads, e.g. electric motors, in the power system are dependent of frequency. When the power system experiences a disturbance in power balance, and the frequency starts to decrease, some loads in the system also start to decreases. This phenomenon is referred as a self-regulation of loads and it is an important power system parameter, as it decreases the need of frequency reserve capacity [3]. It is not possible to know the amount of self-regulation of loads in a power system exactly, but it can be approximated for example from disturbance frequency deviation data.

With the use of frequency reserves, the power system is able to maintain the system frequency at an acceptable level at all times. The hierarchy of use of frequency reserves starts from the fast-acting containment reserves to produce immediate frequency stabilization followed by the restoration reserves to release the FCRs back in to use and finally bring the system frequency back to nominal. The use of frequency reserves during frequency deviations is explained in more detail in the next section.

2.3 Frequency control action

When a large production unit is disconnected from a power system due to a disturbance, the balance between generation and loads sees an immediate change. As the electrical energy consumed in the power system is greater than the production, the system frequency starts to decrease as the remaining generators begin to decelerate. The power system frequency control tries to restore the system frequency back to nominal as soon as possible. In Figure 2.5 is shown the system frequency, load and the activation of real power reserves as a function of time when a large production unit is disconnected from a power system.

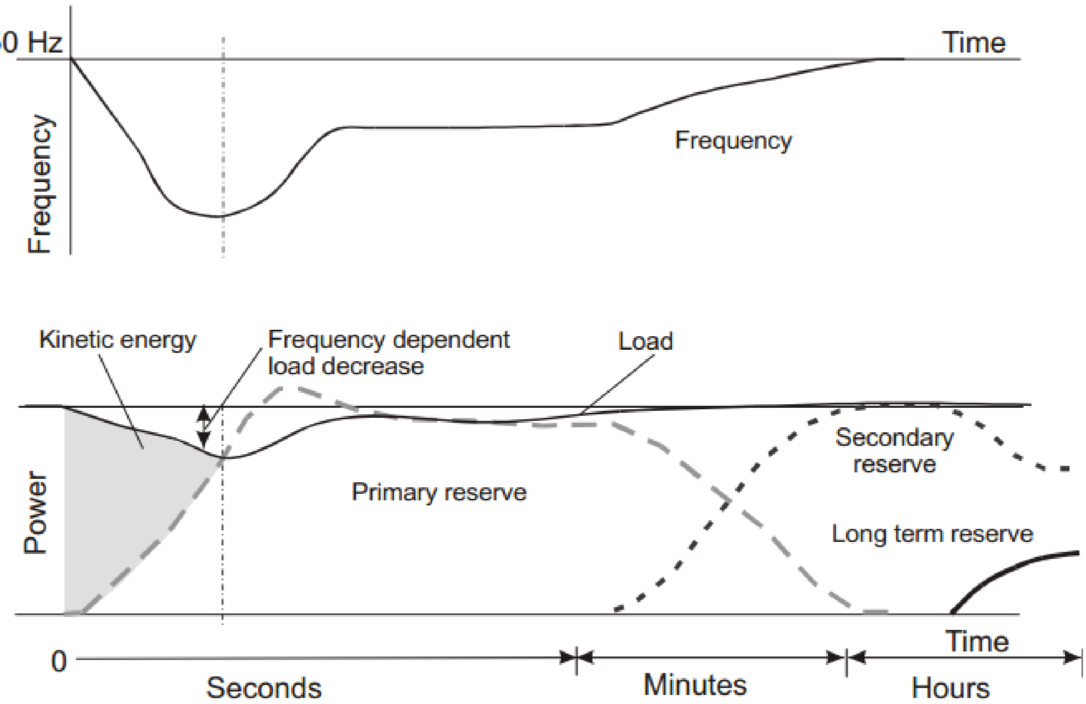

Figure 2.5 *System frequency, load and the activation of real power reserves as a function of time when a large production unit is disconnected from a power system [10]*

Before frequency control

The system frequency decreases almost linearly and the rate of change is dependent on the combined amount of the generators' inertia. With the decrease of frequency, the system sees some self-regulation, as the frequency dependent loads decrease.

Seconds

The primary control action in the form of FCR activates and quickly stabilizes the system frequency. After the use of primary reserves, a steady-state error is still present in the system frequency. The primary control action typically activates in 5 to 10 seconds.

Minutes

The secondary control action in the form of FRR activates to restore system frequency back to nominal. With the activation of the secondary reserves, the primary reserves are released from use and back to full capacity. The secondary control action typically restores the system frequency within 15 minutes.

Hours

The tertiary control in the form of RR can be used, if new disturbances are anticipated. The replacement reserves are manually activated in some hours.

The detailed use of frequency reserves is different between the different synchronous areas in Europe as there are multiple power system specific design parameters that need to be taken in to account. The next chapter presents the application of frequency control in the Nordic power system and discusses the frequency stability obligations of the Finnish TSO, Fingrid.

3. NORDIC POWER SYSTEM

In this chapter, the specifications and frequency control of the Nordic power system are presented. In the first part, the general features regarding the structure and electricity production of the Nordic power system are discussed. In the second part, the operation of the electricity market is explained. In the last part, the application of frequency reserves and frequency control in the Nordic power system is revised.

3.1 Structure of the Nordic power system

The Nordic power system is one of the five regional groups that operate in Europe. The Nordic power system's synchronous area consists of the electricity networks in Finland, Sweden, Norway and East Denmark. These countries' TSOs also form the Regional Group Nordic (RGN) that operates under ENTSO-E. The main purpose of the RGN is to conduct and promote the cooperation between the involved TSOs with the aim of ensuring a reliable operation, optimal management and technical development of the Nordic synchronous area, especially in the areas of system security and electricity market operation [7]. In the Figure 3.1 is shown the Nordic power system (green) and the maximum cross border capacities of the tie lines between countries in 2012.

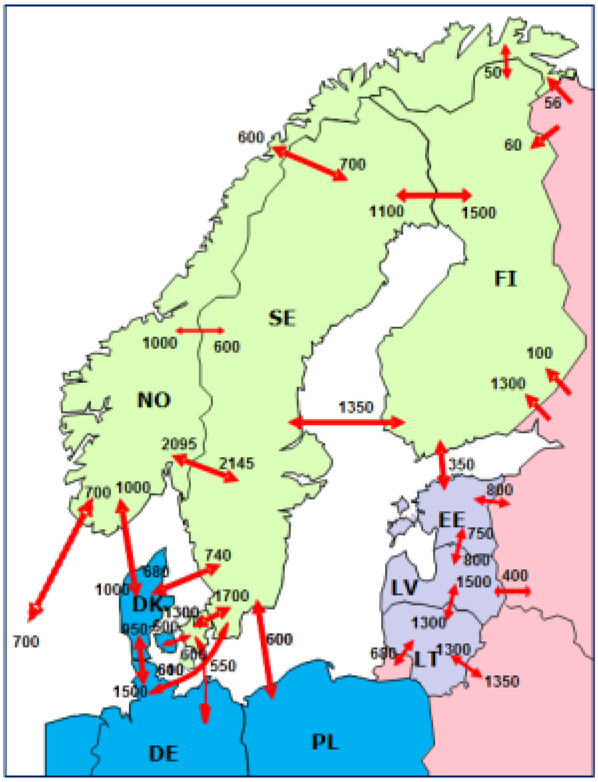

Figure 3.1 *The Nordic power system with the maximum cross border capacities in 2012 [23]*

Unlike some other power systems, e.g. in Continental Europe, the Nordic power system does not have a heavily looped structure, as the Baltic Sea and the Scandes divide it in to partitions. In addition, the energy production and consumption in Scandinavia is quite separated, as the majority of the consumption is located in the southern parts, but a decent share of the produced energy (namely hydropower) is located in the northern parts of the region. The energy production is diverse in the Nordic power system. In Figure 3.2 is shown the generation mix of the Nordic countries within the synchronous area.

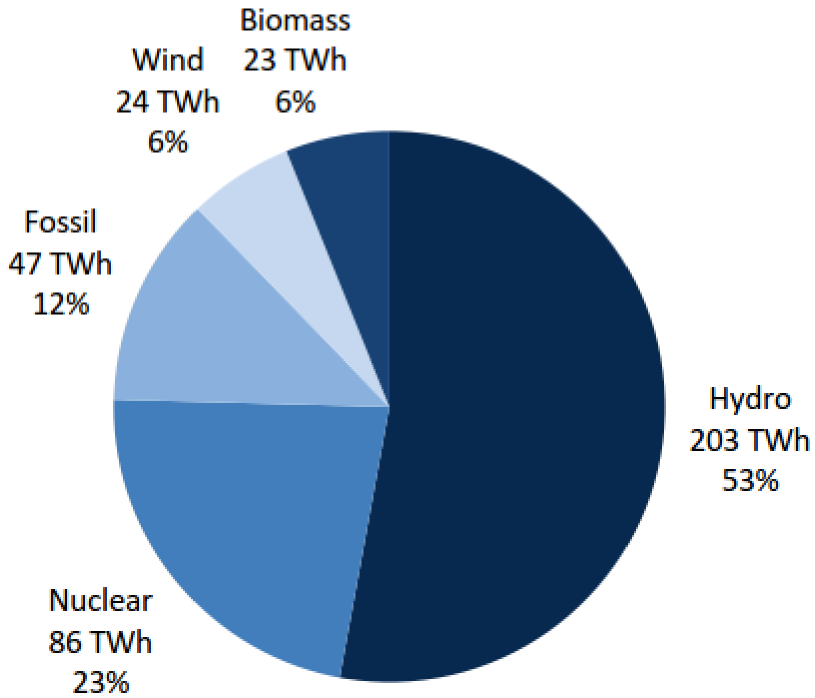

Figure 3.2 *Generation mix of the Nordic countries in 2014 [18]*

From Figure 3.2 can be seen that the Nordic power system is reliant of hydropower as it covers over half of its yearly energy production. While hydropower does offer a flexible form of energy production, that can be easily applied for frequency control, the amount of electricity produced by it is greatly dependent on the amount of rain the region sees yearly. Due to this natural factor, that cannot be affected, the price of electricity in the Nordic electricity market has a high volatility [19]. Furthermore, the divergence of production and consumption, as well as the geographical features of the Scandinavia, has created bottlenecks for the transmission of power in the Nordic power system, which has caused the synchronous area to be divided in to several price groups in the electricity market. These concepts are discussed in more detail in the next section.

3.2 Nord Pool electricity market

Nord Pool (previously Nord Pool Spot) is the largest operating market for electrical energy in Europe. The history of the market begins in the 1990, when the Energy Act formed the basis for deregulation of the electricity markets in Nordic countries. The framework for an integrated Nordic electricity market contracts was made to the Norwegian Parliament in 1995, and by the year 2000 all countries of the Nordic synchronous area were integrated as a part of the market. Since then, the market area has spread to the Baltic region, Germany and UK. The Nord Pool electricity market has seen an ongoing development during its twenty-some years of operation and today the Nord

Pool runs the leading electricity market in Europe, offering both day-ahead and intraday markets to its customers. [17]

For the electricity producers and consumers operating in the market area, Nord Pool offers the day-ahead market (Elspot) and intraday market (Elbas) as electricity markets. In these markets, the contracts always finalize in an actual transmission of electricity. In the day-ahead market, electricity sellers and buyers (called members) make bids for the next day. The bids are made for the amount of electricity the member can deliver or wants to buy and for what price. These bids are made for every hour of the day and after the bidding closes, at 12:00 CET, the hourly electricity prices are computed based on the supply and demand, like shown in the Figure 3.3. [17]

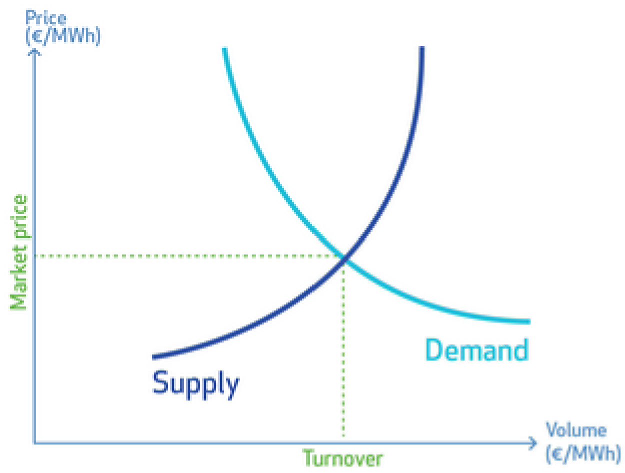

Figure 3.3 *The formation of market price based on supply and demand [17]*

The intraday market is used to supplement the day-ahead market. It helps to secure the necessary balance between the supply and demand in the case where members fail to fulfill their contract made in the day-ahead market. The intraday market is a continuous market and the trading for power is locked one hour before delivery. The Nord Pool electricity market also has a financial market, where financial contracts are used for price hedging and risk management. In the Nordic region, financial contracts are traded through Nasdaq Commodities. In the electricity market, the price for electricity is not the same for everyone, as the Nordic market area has been split into different price regions. [17]

The Nordic electricity market integrates all the different members within the synchronous area to be a part of the electricity exchange business. However, as the energy consumers and producers can be located anywhere in the power system, the actual realization of power transfer has to be done in the terms of power system stability. This has caused the Nordic market region to be split up into different price regions based on the load capacity between the regions tie lines. In Figure 3.4 is shown the different price regions currently used in the market area.

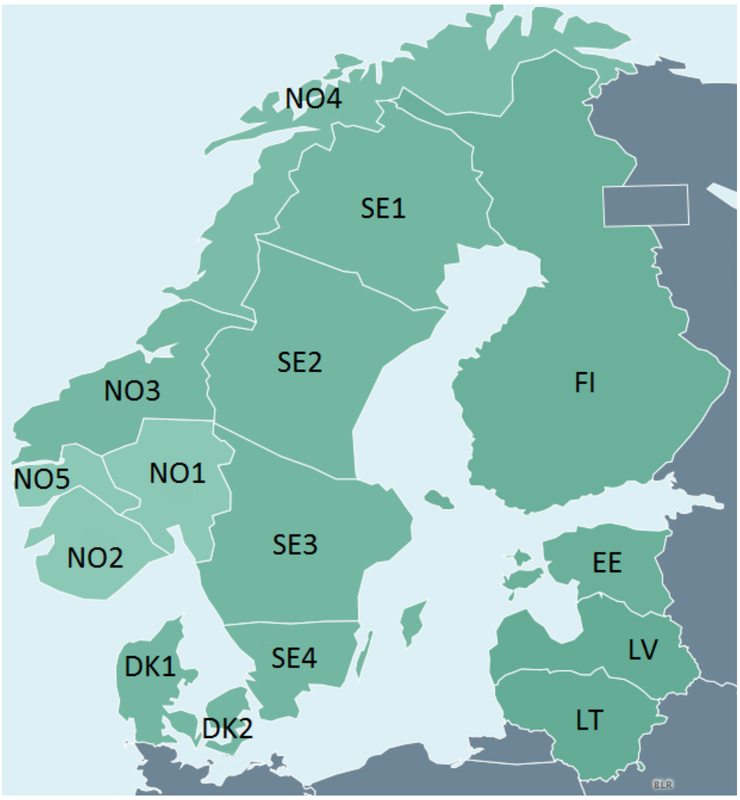

Figure 3.4 *Different price regions in the Nordic power market [17]*

The price of electricity in these regions changes all the time depending on the energy consumption. By dividing the market area in to different price regions, the regional price compared to the system price gives an accurate indication of the production and loading capacity in the area. In Figure 3.5 is shown the number of Nordic price areas in 2012.

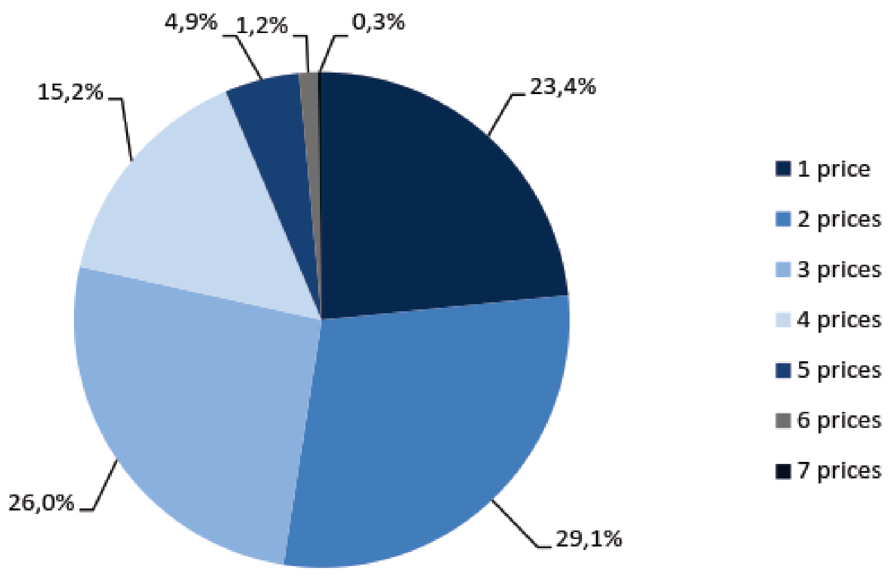

Figure 3.5 *The number of different prices for electricity in the Nordic power market in 2012 [18]*

From Figure 3.5 can be seen that the Nordic power market area shared the same price for 23.4 % of the time, and for 52.5 % of the time, there were two prices for electricity. In 2013, Finland and Sweden shared the price for electricity 78 % of the time. The electricity market is also used as a part of a power balance maintenance in the Nordic countries as the TSOs manage a market, called a balancing power market, as an important part of their power balance management.

As the TSOs do not have their own regulating capacity, a balancing power market is maintained. In the balancing power market, the owners of electricity production or disconnectable loads can submit bids in regards of their capacity that can be used for regulation. The bids can be for up-regulation, if there is a need to increase production or decrease consumption, or for down-regulation, if the production needs to be decreased or consumption needs to be increased. For the bidding, a Nordic regulation curve is formed for every hour based on the need for regulation. The bids have to be placed at least 45 minutes before the regulation hour and the capacity needs to be able to activate within 15 minutes of the activation order. After bidding, the offers for regulation are arranged based on their price. For up-regulation, the prices are arranged from the lowest offer first, and for down-regulation, the bids are arranged from the highest offer first. The TSOs then either sell or buy electricity from the bidders, based on the regulation action. If the power transfers are not limited by a cross-border capacity, the regulation services are used in the price order. In other cases, the TSOs use the balance service as efficiently as possible without compromising power system stability. The balancing power market is used as a part of the frequency reserves in the Nordic power system. As the power balance of the power system is affected by all the different parties connected to it, it can be complicated for the TSO to fulfill its obligation of maintaining the system stability. Therefore, the different electricity producers and consumers using the power system are required plan their operation within the rules of a balance model. [8]

The TSO is responsible for maintaining the power balance in its power system. To achieve this goal, a balance model is used. The goals of the balance model is to ensure the balance between electricity production and consumption and to determine the electricity usage of the different parties (producers, sellers, buyers) operating in the electricity market. For this purpose, the different parties of the electricity market are obligated to report their estimates for the produced or consumed electricity for each hour of the day. As these reports are only estimates, there will always be deviations compared to the actual energy transfers that are realized during the hour. These differences, between the balance reports and the realized energy usage, are later settled in an imbalance settling between the TSO and the involved parties. In the imbalance settling, the TSO either sells or buys the surplus or deficit energy with a predetermined price. The balance model is a tool that makes the power balance management possible for the TSOs. Obligating the different parties to define their electricity usage gives the TSOs a good understanding about the state of the power system for every hour of the day. The balance reporting also benefit the different parties operating in the market area, as an important part of their operation is to design the efficient usage of electricity based on the production and consumption in the power system. The balance model also helps to define the use of frequency reserves for the Nordic power system.

3.3 Frequency reserves and control in Nordic power system

The total capacity of the frequency reserves in the Nordic power system is divided between the involved countries' TSOs and the obligations for maintaining frequency reserves have been agreed in the System Operation Agreement [8]. In the following segment is presented the use and requirements for frequency reserves for the Nordic power system.

Frequency Containment Reserve for Normal operation (FCR-N)
In the Nordic power system, a total of 600 MW of FCR-N is constantly maintained. This jointly maintained reserve is divided between the Nordic TSOs in relation to the total yearly consumption of electricity in each country. FCR-N is used to maintain the frequency between 49.90 – 50.10 Hz. The unit that provides the reserve for FCR-N has to be able to operate linearly within this frequency range with a maximum dead band of 50 ± 0.05 Hz. FCR-N needs to be able to fully activate within 3 minutes following a step-wise change of 0.10 Hz in frequency. [9-10]

The Frequency Containment Reserve for Disturbances (FCR-D)

The FCR-D is dimensioned by following the N-1 – criteria. From this criteria, the power system needs to be able to withstand a disturbance, where the largest production unit needs to be disconnected (dimensioning fault), without the steady-state frequency deviation exceeding 0.5 Hz. Currently the largest Nuclear power plant in operation in the Nordic power system is in Sweden (Oskarshamn 3, 1400 MW). Later, the largest Nuclear power plant in the system will be the Olkiluoto 3 in Finland (1600 MW), which is currently under construction. The FCR-D in the Nordic power system is set weekly to correspond to the worst-case scenario fault, reduced by the self-regulation of loads in the system. In the Nordic power system, the self-regulation effect of frequency dependent loads is considered to be 200 MW during the disturbance and a total of 1200 MW of FCR-D is maintained in the system. The production unit that provides the reserve for FCR-D has to be able to operate linearly so that the reserve begins to activate when the system frequency decreases below 49.90 Hz and is fully activated when the frequency is 49.50 Hz. In 5 seconds, 50 % of the FCR-D should be activated, and the reserve needs to be fully activated in 30 seconds following a step-wise change of -0.50 Hz in the frequency. If the unit providing the reserve for FCR-D is a disconnectable load, the reserve needs to be active within the limits shown in Table 3.1.

Table 3.1 *Disconnect times for relay-connected loads used in FCR-D [7]*

Frequency (Hz)	Disconnect time (s)
≤ 49.70	≤ 5
≤ 49.60	≤ 3
≤ 49.50	≤ 1

The owner of the reserve can connect the load back in to the power system, when the system frequency has been at least 49.90 Hz for 3 minutes. [9, 10]

Frequency Restoration Reserve – Manual (FRR-M)

Each TSO needs to maintain enough Manual Frequency Restoration Reserve (FRR-M) to cover a dimensioning fault in its own subsystem. [8]

Frequency Restoration Reserve – Automatic (FRR-A)

The use of FRR-A in the Nordic power system began in 2013. The reserve was targeted for specific morning and evening hours, when the energy consumption is high and the maximum amount of FRR-A in the power system was 300 MW. As of 2016, the use of this reserve was discontinued, as the market infrastructure around it did not see the predicted development. [8]

Replacement Reserves (RR)

Replacement reserves are not in use in the Nordic power system. [8]

For Finland, the reserve obligations in 2016 are shown in Table 3.2.

Table 3.2 *Frequency reserve obligations for Finland in 2016 [8]*

Reserve product	Obligation
FCR-N	~ 140 MW
FCR-D	~ 260 MW
FRR-M	~ 880 MW

For the procurement of the reserves, each TSO can choose where they acquire the reserves and reserves can also be traded between the countries. However, at least 2/3 of the reserves need to be maintained nationally, so that the system frequency can be can be controlled in the case of subsystem islanding [8]. In Table 3.3 is shown the procurement sources for Fingrid's reserves in 2015.

Table 3.3 *Frequency reserve procurement sources for Fingrid in 2015 [8]*

Reserve product	Procurement channel
FCR-N	Yearly market Hourly market Other Nordic countries Vyborg DC link Estonia, Estlink 1 & 2
FCR-D	Yearly market Hourly market Other Nordic countries Disconnectable loads
FRR-M	Balancing power market Fingrid's reserve power plants Leasing power plants Disconnectable load

The Frequency Containment Reserves are mainly covered with the yearly and hourly contracts. These contracts are made between Fingrid and parties with generation capacity. For the FCR, especially hydropower is used as a reserve as it provides a fast control action with low price [1]. Steam turbine and gas turbine power plants are also compatible for fast frequency control. Fingrid can also use the DC connections from Estonia and Russia for the FCR [3]. For the Frequency Restoration Reserve, majority of the obligated reserve amount is covered with Fingrid's own power plants and approximately one fourth of the reserve capacity is from power plant leasing contracts. These power plants are not used for commercial electricity but are kept on standby. Fingrid covers the cost of maintaining the reserves through balance and grid service tariffs. [8] While each of the Nordic countries maintain their own reserves, the Nordic power system is used as a single entity for the frequency control.

As the frequency is shared within the synchronous area, the frequency control process is a group effort between the involved countries. In the Nordic power system, Sweden and Norway are responsible for the frequency control and maintaining the system time error within the agreed limits. For maintaining the frequency stability in the synchronous area, one important factor is the cross-border power transfers, as the transmission cables have capacity limits. For example, if the system frequency is nominal and the power capacity between Finland and Sweden is not limited, then Finland does not try to control frequency deviations unless ordered by the Swedish TSO. The problematic situation occurs, when the power transfers between the countries is in limit, and the electricity production needs to be changed to maintain system operation, regardless of its effects to frequency. Because of this structural feature, the frequency in the Nordic power system needs to be maintained close to nominal, while at the same time the system reliability cannot be compromised with overloading the cross-border power transmission. In the Continental Europe, the frequency control of the synchronous area and the cross-border power transfer control is done simultaneously with an automated control system. [3]

When the synchronous area contains a large amount of synchronous generators and is heavily looped, like in the Continental Europe, the frequency control process needs to be fully automated. The automated control system, referred as *automated generator control* (AGC), automatically controls the system frequency within the synchronous area and keeps the cross-border transfer within agreed limits. The AGC is needed to prevent the generators' control systems to cause a *loop-flow*. In loop-flow, a change in one generator's output power causes a power loop, where other generators try to compensate for the change in power in a quick succession and causing a useless power loop in the system as the generators' speed controllers are effectively competing against each other. In the Nordic power system, only the primary control is automated and the secondary control is operated manually. The secondary control can be achieved without AGC due to the structure of the power system does not contain large amount of looping over a massive land area. [3]

4. DEMAND RESPONSE FOR POWER SYSTEM FREQUENCY CONTROL

In this chapter, the use of demand response for frequency control is discussed. In the first segment, an overview of the demand response is given. In the second segment, the potential of demand response technologies to the TSO is discussed in more detail. In the third segment, the potential of different load types that can be utilized in demand response is reviewed. In the last segment, a brief look at the electric space heating in Finland is presented.

4.1 Demand response

In today's power system, we have very little control over the customers' loads. Therefore, the energy demand of the power system can see a lot of variance throughout the day and the power balance is primarily maintained by matching the generators' output power with the demand. However, being able to reduce the peak power demand or shift energy usage to a different time would be beneficial to all of the members operating in the electricity market. Currently, the incentivization of customers to change their energy consumption habits has been limited. Demand response seeks to improve this utilization of demand side loads in power system operation.

Demand response (DR) can be defined as the changes in electricity usage by end-use customer from their normal consumption patterns in response to changes in the price of electricity over time. Furthermore, DR can also be defined as the incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized. DR includes all intentional electricity consumption pattern modifications by end-use customers that are intended to alter the timing, level of instantaneous demand or total electricity consumption. [16] The possible benefits of large-scale use of DR for different members operating in the electricity market are listed in the following:

Customer
The electricity end user can benefit from DR through energy cost optimization by shifting the time of use of electricity from a higher price point to a lower price point. DR can also be used to optimize the use of customer energy production (e.g. solar power) and reduce peak power consumption. [11]

Electricity retailer

Electricity retailers can use DR in planning of electricity purchases, to improve their balance model management, to take advantage of bids in the balancing power market and in development of their products and business. [11]

Distribution network operator (DNO)

DNOs can utilize DR for improving their long-term network planning by having a better understanding of power demand development in their network. DR can also be used to reduce the peak power in their network during higher consumption periods. [11] Additionally, load control can be utilized to improve power system security in the case of islanding.

Transmission system operator (TSO)

The TSO can use DR as a part of their frequency reserves for normal operation (FCR-N) and disturbances (FCR-D). Furthermore, load control can be used to provide capacity to the balancing power market. DR may also offer more flexibility in dealing with severe power shortages. [11] DR also can possibly be used to create a new type of reserve through the use of very fast load control. The TSO's utilization of DR is discussed in more detail in the next segment.

Product/Service providers

Large scale use of DR also opens a new market for various new products and service providers. [11]

While the use of DR can be seen as a benefit for all of the different members operating in the electricity market, it can also create conflicting interests. For example, the DNOs interest in reducing peak powers in its network can conflict with the customers' or electricity retailers' interests when they are operating based on the electricity market price. Therefore, it still requires a lot of work in improving the legislation and definitions of the use of DR. Nevertheless, with the ongoing development, it is believed that large-scale use of DR is a possibility in the near future. [11]

4.2 Demand response for TSO

As it was discussed in the previous chapter, maintaining power system's frequency as close to nominal as possible is essential for its operation. Currently, frequency control is mostly done in the supply side, as demand side management is not heavily utilized. With the ongoing development of DR, the possibilities of using end-user load control for the purpose of frequency control have been explored as well. With the proper technological implementation, the TSO could add flexibility and robustness to its frequency reserves that would improve the power system's operation. Being able to expand the frequency control to the demand side may also be needed, as the conventional power system operation is seeing a possible infrastructural change in the near future.

In the efforts of reducing energy production's role in the climate change, the investments and research regarding the use of renewable and pollution free energy production has significantly increased in the last two decades. From this, the increasing utilization of solar power (photovoltaic, PV) and wind power has been a key focus in many countries' energy production development. However, the large-scale use of this type of intermittent power production is not that straightforward as it complicates frequency control. While both wind power and PV power can technically be used for down- and up-regulation [20], they will ultimately cause a decrease in the power system's total inertia, as they do not utilize a large synchronous generator for their power production. When the power system's inertia decreases, the system frequency is more susceptible for rapid changes when the power balance is disturbed.

In the Nordic power system, where majority of the frequency control is done using hydropower, demand side control is also being seen as an opener for more competition in the reserve markets. In a study, where available capacity for load control was compared to reserve capacity prices in the electricity market, the economic potential of load control to be used as frequency reserve was significant [11]. Comparing the use of load control for different market places, the economic potential of reserve market was as high as 17 times of that of Elspot, depending on the year [11]. This means that the frequency reserve capacity, that DR can offer, is economically very competitive and would be able diversify the available reserves in the market.

The customer side load control as a technology also has the possibility to be utilized as completely new type of reserve. Currently, the fastest acting form of frequency control is the synchronous generator speed control. In a case of N-1 –type fault, this fast frequency control usually activates within 5 to 10 seconds. Before the generator speed control is able to react to the power imbalance, only the power system's inertia dictates the rate of change of frequency. However, with load control, it is possible to achieve a much faster reaction time. If a localized control action can be realized and the control is done through a power electronic interface, it is technically possible to reach sub-second activation of the control. In Figure 4.1 is visualized the use of very fast load control as a part of the frequency control scheme.

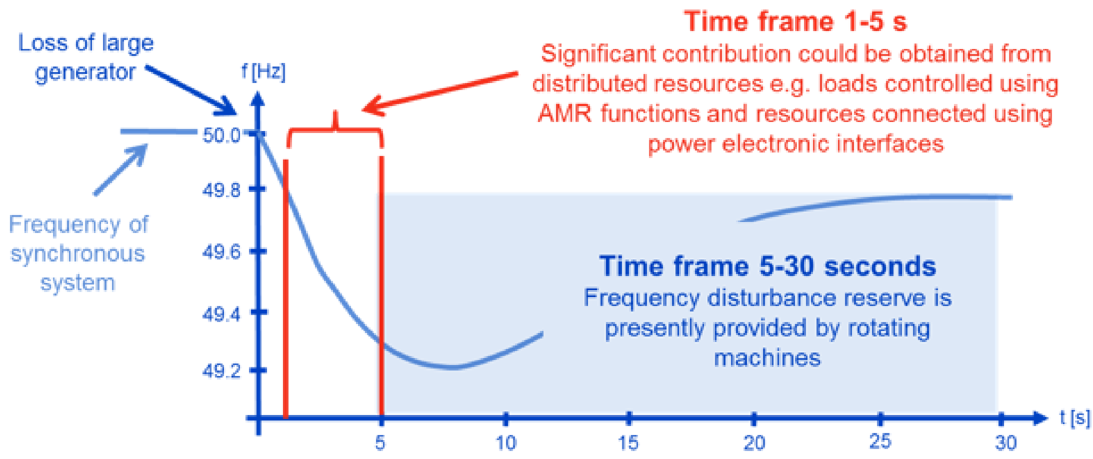

Figure 4.1 *The use of customer side load control for very fast frequency control [20]*

The very fast load control as a frequency reserve is lucrative, as it can help alleviate the loss of power system inertia caused by the use of intermittent renewable energy production. Nevertheless, while DR has a lot of potential to be used in frequency control in the future, there are challenges in its integration process to be a part of the current frequency reserves.

Currently, in order to use load control as a part of the frequency reserves, it needs to fulfill the same requirements that are used for supply side frequency control technologies. In Table 4.1 is listed the current requirements of minimum control capacity and activation times for different frequency reserves.

Table 4.1 *Minimum control capacity and activation time requirements for different frequency reserves [11]*

Market	Minimum control capacity (MW)	Activation requirements
Balancing power market	10	15 min
FCR-N	0,1	3 min from +/- 0,1 Hz deviation from nominal
FCR-D	1	30 s when < 49,7 Hz 5 s when < 49,5 Hz

From the requirements shown in Table 4.1, the minimum control capacity can be an aggregation of smaller capacities so it should not be a limiting factor for the utilization of load control as a frequency reserve [11]. However, the frequency reserve requirements have a strict obligation for the activation times for all of the capacity that is dedicated to the reserve. This makes the utilization of load control as frequency reserves more challenging, as most of the load types that can be used for load control have varying amounts of uncertainty in their availability for use. This makes the demand side frequency control technology to be very different from the supply side technologies.

4.3 Potential of different load types to be utilized for load control

Not all electrical loads are compatible to be used for load control. In general, the control of the loads should not cause a negative experience for the customer. This means, that the loads that are to be used for load control, should be relatively insensitive to their time of use. For example, traditional residential indoor lighting is not generally suitable for load control, as the effects of the control are instantaneous, but electrical space heating can be used for load control, as the effects of the control have a longer delay. The important characteristics of the loads, which can be used for load control, are the following:

Available capacity
The available capacity of the electrical load is an indicator of the size of the reserve that load can create for load control. Having an understanding of the load capacity can be used to help with prioritizing the development of the load control technology.

Time of use (day/season)
Majority of different electrical loads are not in use all the time. Some loads are only used at a specific time of the day (e.g. car block heating) or only during a specific season (e.g. space heating during the heating season). In addition, thermostat controlled heating loads turn on and off throughout their time of use. Knowing these uncertainties regarding the time of use of the loads can be used to design a better overall load control strategy.

Load peak after control action
Using load control for down-regulation can lead in to a loading spike in the power system after the control action. This is because if the control action lasts long enough, more loads turn on after the control action than was turned off by the control action. Load peaking is prominently an attribute of thermostat controlled loads.

Technology of load control
The technology that is need for the load control varies between different load types. The load control technology that is needed to utilize DR in this regard can be a key factor to take in to consideration when DR technology is being developed.

Down-regulation/Up-regulation

Typically, up-regulation is the main talking point with load control as it is the characteristics of consumption of energy that causes a lot of problems for the power system's operation. However, using load control for down-regulation should also be considered, as it may become more relevant in the future power system operation.

From the load types that are considered to be suitable for load control, an estimation of their potential was studied in [11]. In this study, the load capacity was estimated by using the following to methods:

1. Using various available statistics (e.g. from Statistics Finland) and calculation tools developed for the surveillance of energy consumption on Finland, the average energy consumption at weekly level for various building groups can be formed.

2. Using available consumption data (e.g. AMR hourly data) and statistics of average installed power ratings of various load types, the available load capacity for different loads can be estimated.

In addition to the installed capacity, the time of use of the loads and the possibility of load peaking after the control action was also estimated. The results of the study are compiled in Table 4.1.

Table 4.1 *Estimated installed capacity, time of use dependencies and after peaks for different load types. Adapted from [11]*

Load type	**Installed capacity (MW)**	**Time of the day**				**Season**				**Load peak after control action**	
		M	A	E	N	Wi	Sp	Su	Fa	Yes	No
Ventilation (no res. build.)	600	**x**	**x**			**x**	**x**	**x**	**x**		**?**
Lighting (no res. build.)	4000	**x**		**x**		**x**	**x**	**x**	**x**		**x**
Snow/ice melting	100	**x**	**x**	**x**	**x**	**x**					
Car block heating	1100	**x**			**x**	**x**				**x**	
Geothermal heating	250										
HVAC	400										
External heating	400										
Street lighting	255			**x**	**x**	**x**	**x**	**x**	**x**		**x**
Greenhouses	300	**x**	**x**	**x**	**x**	**x**			**x**		**x**
Electric space heating	5000	**x**	**x**	**x**	**x**	**X**	**x**		**X**	**x**	
Water heating	1500				**x**	**X**	**x**	**x**	**X**	**x**	
Storage heating	1550				**x**	**X**	**x**		**X**	**x**	
Sauna stove	9000			**x**	**x**	**x**	**x**	**x**	**x**	**x**	

M = Morning, A = Afternoon, E = Evening, N = Night
Wi = Winter, Sp = Spring, Su = Summer, Fa = Fall
no res. build. = no residential buildings

Electric heating

Electric heating currently has the highest potential of all load types to be used as a demand response resource. Electric heating is utilized the most in small houses and row houses. In addition, the use of electric heating in summer cottages has increased in the last two decades. The electric heating can be divided between space heating, storage heating and water heating. The total installed power for electric heating systems is estimated to be 5000 MW for space heating, 1500 MW for water heating and 1550 MW for various storage heating systems.

Heat pumps

The use of heat pumps has seen a significant increase in the 2000s. There are approximately 600000 heat pumps in use in Finland. About 500000 of the heat pumps are low power rating HVAC units and about 50000 are geothermal heating units. The total power of installed heat pumps is approximately 1050 MW, where 250 MW is from geothermal heating, 400 MW is from HVAC and 400 MW are from external heating units.

Sauna

There are about 2 million saunas installed in residential buildings from which about 1.5 million are electrically heated. It is also estimated that the number of saunas is increasing at a rate of 25000 per year. The combined power of the sauna stoves is estimated to be 9000 MW. Saunas create a significant demand response resource, but their control is limited by the time and length of their use.

Electric car block heating

During the cold season, electric car block heaters are heavily used in Finland. There are an estimated 1.5 million outlets for car's block heaters. Majority of the outlets are installed for apartment buildings, row houses and work places. During the coldest weeks of the year, it is estimated that the electric car heating creates a 1000-1100 MW load. Generally, car heating is used for 1 – 2 hours daily per car and the time of use consistently is in the night and morning hours of weekdays.

Street lighting and greenhouse lighting

The lighting of streets and greenhouses yield a decently potential demand response resource. Currently, the total power of street lighting is estimated to be about 255 MW, based on the yearly total energy use (900 GWh) and total time of use (4000 h) of the street lighting. For greenhouses, the total power used for lighting is approximately 300 MW. This estimation is based on statistics of total greenhouse area (4.3 million m^2), typical lighting power per area (100 – 250 W/m^2) and the time of use different types of crops sees yearly (25 – 100 %). As these statistics contain variance this estimation of the total greenhouse lighting power is difficult to do accurately.

Commercial, office and education buildings

Commercial, office and education buildings offer an interesting demand response resource with the power used for their ventilation, cooling, lighting and various snow/ice melting systems. However, estimating the control capacity of these buildings is challenging, as these building's construction design varies a lot. The estimates for the control capacity for these buildings were based on building statistics from Statistics Finland. The total power used by these buildings was approximately 410 MW for ventilation, 340 MW for cooling, 1000 MW for lighting and 100 MW for snow/ice melting systems used for roofs and gutters. The ice/snow melting systems used for various pipes and ramps was not in the estimates.

What was not discussed in this study was the various cooling loads that would be suitable for load control. These cooling loads consist of different household and industrial fridges and freezers and larger industrial storage cooling. These load types should be compatible to be used in load control under the same basis as heating loads can be used for load control. Other topic that was not brought forward in this study is the loads' capability for down-regulation. For most of the loads discussed in the study, it should be possible to utilize their down-regulation potential a lot more easily than their up-regulation potential. Furthermore, the time of use of the loads that is shown in Table 4.1 can only be considered to be true right now. As the penetration of the DR technologies increases, and the smart uses of electricity increases, it is no doubt that it will have an effect of the times of uses that electrical loads see in the power system. What can be concluded from this study is that currently, the electric space heating loads offer the single most potential to be used for load control out of all of the other load types. Electric space heater loads have the highest installed capacity out of the loads studied, they are in use for most of the year, they can be utilized for up-regulation and the technology for their control is relatively easy to realize. Therefore, in this master's thesis, the focus on the aggregated load modeling is in the space heater loads in Finland.

4.4 Electric space heating in Finland

The three major factors that affect the choice of heating system for a building are its use, size and location [9]. A residential building requires a different amount of heating than a storage building. The size of the building affects the amount of energy needed for heating. The location of the building can also limit the options for choosing a heating system, as not all heating systems are available in every location. Different heating systems are generally separated by their installation and energy costs. As larger buildings require more energy for heating, the cost of energy is usually the key factor when choosing the heating system [9]. For smaller buildings with low energy use, the price of installation becomes an important factor. An electric heating system is typically easy to use and effective source of heat with a low installation cost but relatively high energy cost. Therefore, electric heating systems have primarily been used for small separated residential buildings [9]. In Table 4.2 is listed building units by their heat source between 1970 – 2015 in Finland.

Table 4.2 *Buildings by heat source in 1970 – 2015 in Finland.[22]*

Heat source	**Year**					
	1970	**1980**	**1990**	**2000**	**2010**	**2015**
Total bld.	837 948	934 845	1 162 410	1 299 490	1 446 096	1 505 138
District	-	48 538	105 608	130 946	164 721	180 749
Oil, gas	320 171	347 498	306 750	320 934	322 279	316 688
Coal/Coke	243 278	11 794	8 753	7 986	6 983	6 789
Electricity	41 872	178 707	357 743	455 752	554 368	578 568
Wood/Peat	429 467	327 230	321 342	292 763	277 553	278 661
Geotherm.	-	-	-	3 397	21 667	46 014

From Table 4.2 can be seen, from the total of 1 505 138 buildings, 578 568 (38.4 %) buildings used electricity as an energy source for heating. This makes electricity the most popular choice of energy for heating in buildings. However, electricity only makes about 20 – 25 % of the total energy used for heating of buildings. In Table 4.3 is listed the use of energy for residential building space heating in 2010 – 2015 in Finland.

Table 4.3 *Use of energy for residential space heating in 2010 – 2015 in Finland [22]*

Heating energy (GWh)	**Year**					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Total	48 765	41 419	45 928	42 739	42 831	40 804
District	15 397	12 619	14 303	13 500	13 127	12 750
Oil, gas	5 759	4 090	4 423	3 753	3 648	3 218
Coal/Coke	4	3	4	3	3	3
Electricity	10 138	9 452	9 895	9 517	9 587	9 464
Wood	14 985	12 464	13 637	12 295	12 465	11 630
Peat	69	42	41	33	30	28
Geotherm.	2 413	2 749	3 625	3 638	3 971	3 711

From Tables 4.2 and 4.3 it can be seen, that there are a high number of electrical heating loads but the capacity of individual loads is relatively small. Furthermore, the use of electricity as an energy source for heating has not seen a lot of increase since the year 2010. This trend is thought to continue in the future, as the energy regulations have become stricter in the last few years.

Currently, in Finland, it is mandatory to have an energy certificate for all new buildings and buildings that are to be sold or rented and that are built after the year 1980 [4]. The energy certificate is used to define the energy efficiency of a building. In the energy certificate, buildings are ranked on a scale of A to G, where A is the highest efficiency class [4]. The energy efficiency of a building is based on the yearly energy need of the building. The key factor, when defining the energy efficiency of a building, is that the different types of energy that are used for heating are valued differently. Currently, the factors for different types of energy used for heating are 1.7 for electricity, 0.7 for district heating, 1 for fossil fuels and 0.5 for renewables [9]. The use of electricity for heating is therefore heavily disincentivized as for example compared to district heating, you would have to use less than half of the amount of energy for heating to get the same energy efficiency class. The use of electrical heating system in newer buildings is still possible, as low-energy houses are increasing in popularity. In low-energy houses, the heat losses are effectively halved by using better insulations and energy efficient ventilation. As the heat losses are lower in a low-energy building, the need for heating energy is also decreased, making the use of electrical heating system a viable option in some cases.

5. LOAD MODEL OF A RESIDENTIAL SPACE HEATER

In this chapter, the aggregated model of an electric, thermostat-controlled space heater is developed. In the first segments, the goals and simplifications of the model are being discussed. In the second segment, the basic thermodynamic model of a building is made followed by detailed definitions of the model parameters. In the last part, the reference model and the aggregated load model is created and tested to confirm the wanted operation.

5.1 Description of the model

The objective of the model is to be able to model the operation of electrical heating loads during the heating period in Finland. However, electric space heating loads are not on all the time, but instead a thermostat is used to control them. Therefore, in order to understand the operation of the heaters, the operation of the thermostat needs to be understood.

A thermostat uses the building's indoor temperature as a control signal to turn the heating system on and off. As the thermostat is not able to keep the indoor temperature at the exact set value, the temperature is allowed to fluctuate around the set point. The thermostat turns the heating system on when the temperature reaches the lowest allowed value from the set value, and turns it off when the temperature reaches the highest allowed value from the set value. In Figure 5.1 is shown the operation principle of a thermostat that is controlling a heating load.

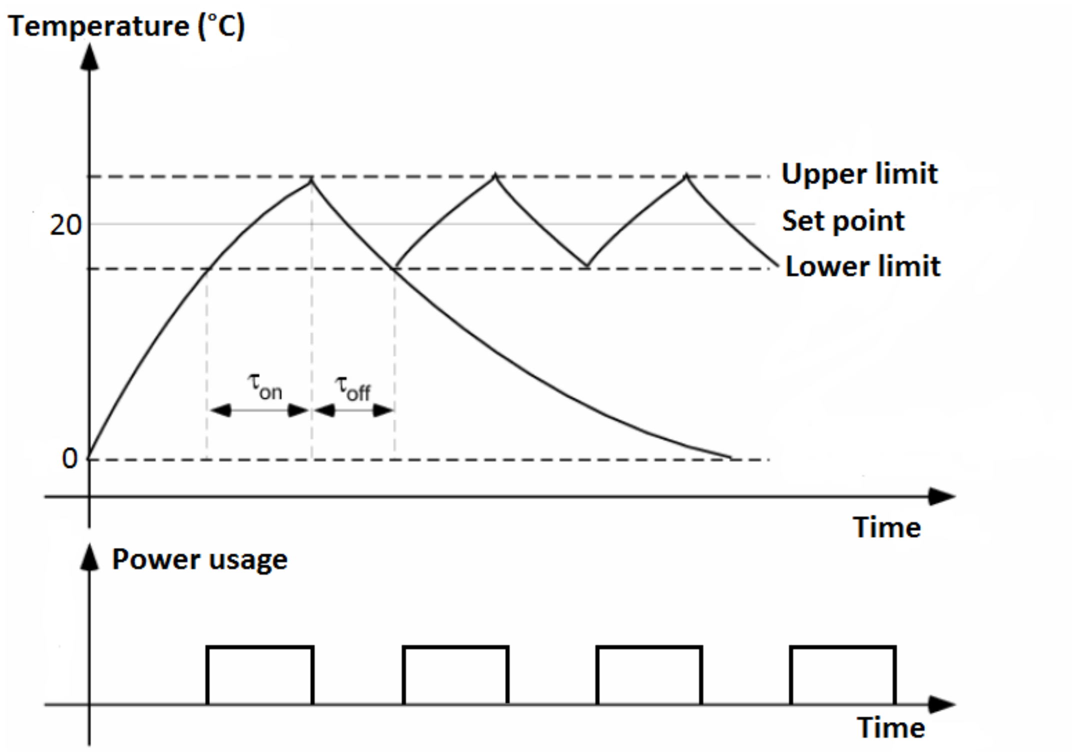

Figure 5.1 *Operation principle of a thermostat controlling a heating load [13]*

From Figure 5.1 can be seen that the indoor temperature represents a triangle wave defined by the thermostat settings. Additionally, the power usage of the heater represents a square wave dependent of the indoor temperature changes. Therefore, the indoor temperature as a function of time needs to be modelled.

5.2 Simplifications of the model

The purpose of the aggregated space heater load model is to be able accurately represent the availability of space heater loads for frequency control in Finland. However, the thermodynamic model, meaning the modeling of the indoor temperature of the building as a function of time, reaches a high level of complexity if done accurately. In an aggregated model, that is supposed to present possibly hundreds of thousands individual heating loads, criticism needs to be taken towards the complexity of the load model. For this model, the following simplifications are used:

Indoor temperature of the building is homogenous
The indoor temperature is never homogenous inside the entire building. This is because air leakage, windows, ventilation and the heating system creates hot spots and airflow that causes variance in the temperature. Furthermore, buildings can have a complex layout of rooms that are different in size and have different purposes (kept in different temperatures). This causes the building also to have inner thermodynamics that makes it

more difficult to model accurately. However, the effect these dynamics have on the operation of a thermostat can generally be considered minimal. This is because it is part of a proper design of the building heating and ventilating systems to minimize these effects in the first place.

Heat gain from the electrical heating system is constant during operation
An electrical heating system is usually a combination of direct heating components (e.g. radiators) and heating components that have a storage capability (e.g. under floor heating). The direct heating components can be thought to heat the building with a constant power when needed. However, the storage heating elements are a lot more difficult to model. Usually, the storage heating elements are heated during the nighttime, when electricity in Finland is cheaper, and are heating the building passively during daytime. This behavior is not easy to predict, as the smart use of electricity increases in popularity. For simplicity, the heat gain from the heating system is considered to be constant.

Heat gain and heat loss from thermal radiation is negligible
During wintertime, large majority of the heat loss is due to the conduction and convection. In addition, the heat gain from the thermal radiation of the sun can be neglected [14]. This is due to the limited daytime in the northern hemisphere.

Thermostat operation is binary
The thermostat in this model is considered to operate using a binary on/off –type control. Other types of thermostats are also used in real life applications, but they are not considered in this model.

With these simplifications, it is possible to build a thermodynamic model of the building indoor temperature as a function of time.

5.3 Thermodynamic model of a building indoor air temperature

We use buildings to isolate an area in efforts to try control its climate. In a building, the physical separator between the controlled and uncontrolled environment is called the building envelope. The building envelope is designed to facilitate resistance to noise, light, air, water and heat transfer. For the purpose of this model, the point of interest is to understand how the building behaves in a cold climate, where the outdoor temperature is lower than the indoor temperature. In order to understand the heat transfer of a building in this environment, we need to look at some basic thermodynamics.

From the zeroth law of thermodynamics, it can be concluded, that two systems are in thermal equilibrium if no heat is flowing between them when a path permeable to heat connects them. Thermal equilibrium is a state that the thermodynamic system spontaneously tries to reach. If the two systems are not in thermal equilibrium, meaning they have different temperatures, heat will transfer between the two bodies in contact. Heat transfers always from the higher temperature system to the lower temperature system via the following three mechanisms. [24]

Conduction is heat transfer via microscopic collisions of particles that causes energy to transfer within a solid material or between substances that are in direct contact of each other. [24]

Convection is heat transfer via a movement of collection of molecules within a fluid (gas or liquid). [24]

Radiation is heat transfer via electromagnetic waves that all matter above the temperature of absolute zero emits to its surroundings. [24]

Heat transfer between the two systems causes the temperature of the higher temperature system to decrease, as the internal energy of that system decreases. However, it is not possible to know the amount of internal energy a body has based on its temperature. This means that even if the rate of heat transfer of the system is known, it is not possible to determine how the temperature of the body changes over time. Furthermore, heat transfer is dependent on the temperature difference between the two systems. This causes the temperature change between two systems that are not in thermal equilibrium to be non-linear. [24]

The change in the temperature over time of a body that is surrounded with a substance of lower temperature can be defined by Newton's law of cooling [24]:

$$\frac{dT}{dt} = -r(T - T_{env}) \tag{5.1}$$

where

$T(t)$	temperature of a body over time, °C
T_{env}	temperature of the environment surrounding the body, °C
r	positive constant, 1/s

The solution to the first-order differential equation described by Equation (5.1) is [24]:

$$T(t) = (T(0) - T_{env})e^{-rt} + T_{env} \tag{5.2}$$

where

$T(0)$	initial temperature of a body at time 0, °C

In the Equations (5.1) and (5.2), the positive constant r is the ratio of heat transfer coefficient H (W/K) and the body's heat capacity C (J/K). The constant r describes the system's internal energy characteristics. The Newton's law of cooling describes the non-linear temperature drop over time of the body [24]. With few modification's, the Newton's law of cooling can be used to define the temperature change that occurs in a building during winter. This type of adaptation was done in [21] by Rautiainen et. al. Similar adaptation is also used as the thermodynamic base model in this thesis.

A building as a simple thermodynamic model is presented in Figure 5.2. In Figure 5.2, T_o (°C) is the outdoor temperature, T_i (°C) is the indoor temperature, C (J/K) is the heat capacity of the building, H (W/K) is the total heat transfer coefficient of the building, P_{loss} (W) is the rate of heat loss through the building envelope and P_{heat} (W) is the rate of heat gain produced by the heating system.

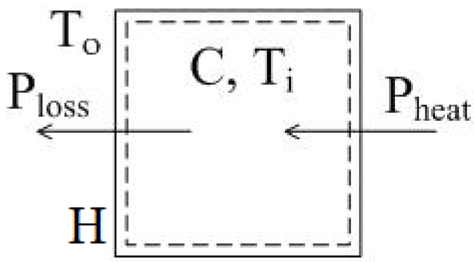

***Figure 5.2** Building represented as a thermodynamic system. Adapted from [21]*

The heat loss through the building envelope is caused by the difference in indoor and outdoor temperature that causes the system to not be in thermal equilibrium. The rate of this heat loss is directly proportional to the total thermal conductance and to the temperature difference across the building envelope [21]:

$$P_{loss} = H(T_i - T_o) \tag{5.3}$$

P_{loss} causes the indoor temperature to decrease over time. The indoor temperature change ΔT_i over a time interval Δt is caused by the decrease in the system's internal energy by the amount of $C\Delta T_i$. In accordance to the conservation of energy principle, the change in the system's internal energy must be equal to the difference between the heating power and heat loss over the same period of time [21]:

$$C\Delta T_i = (P_{heat} - P_{loss})\Delta t \tag{5.4}$$

Equation (5.3) can now be substituted for Equation (5.4):

$$C\Delta T_i = (P_{heat} - H(T_i - T_o))\Delta t \tag{5.5}$$

Dividing both sides with Δt, rearranging and letting the time interval approach zero ($\Delta t \rightarrow 0$), we get a simple ordinary differential equation [21]:

$$C\frac{dT_i}{dt} + HT_i = P_{heat} + HT_o \tag{5.6}$$

Equation (5.6) describes the indoor temperature dynamics. If C, H, P_{heat} and T_o are assumed to be constant with respect to time, an analytical solution of the ordinary differential equation initial value problem, formed by (5.6) and the indoor initial temperature value $T_i(0)$, is [21]

$$T_i(t) = \left(T_i(0) - \frac{P_{heat}}{H} - T_o\right)e^{-\frac{H}{C}t} + \frac{P_{heat}}{H} + T_o \tag{5.7}$$

Equation (5.7) describes the change in indoor temperature T_i over time, when the initial indoor temperature $T_i(0)$, heating power P_{heat} of the heating system, total heat transfer coefficient H of the building envelope, outdoor temperature T_o and specific heat capacity C of the building are given. Equation (5.7) is a representation of the Newton's law of cooling (Equation (5.2)) that allows the modeling of the heat gain through the heating power P_{heat}. For numerical computing, the values of these parameters need to be determined.

5.4 Defining the parameters of the model

In the previous segment a simplified model for the indoor temperature of a building as a function of time was derived. For numerical computing of the model, the following parameters need to be defined:

- $T_i(0)$ – initial indoor temperature
- T_o – outdoor temperature
- P_{heat} – heating power of the electric heating system
- H – total heat transfer coefficient of the building
- C – heat capacity of the heated mass inside the building

From these parameters, the initial indoor temperature $T_i(0)$ and the outdoor temperature T_o can be arbitrarily chosen for different computations. In addition, the thermostat parameters (set point, upper limit, lower limit) need to be defined to model the operation of the space heaters.

5.4.1 Building heat transfer coefficient

Every residential building in Finland needs a heating system to be able to maintain the indoor temperature during wintertime. The heating systems for buildings are designed based on an estimated heat loss that the building experiences during the cold time of the year. This heat loss can be calculated based on the guide provided by the Finnish Ministry of Environment [14]. From this guide, a following procedure is used for calculating the total heat transfer coefficient of a building:

The net heating energy need for space heating of a building is calculated with the Equation (5.8).

$$Q_{heating,spaces,net} = Q_{space} - Q_{in.heat} \tag{5.8}$$

where

$Q_{heating,spaces,net}$	net heating energy need for space heating of a building, kWh
Q_{space}	heating energy need for space heating of a building, kWh
$Q_{in.heat}$	other heat loads that are used for space heating, kWh

The building heat transfer coefficient is calculated with Equation (5.9).

$$H = \frac{Q_{space}}{(T_i - T_o)\Delta t} 1000 \tag{5.9}$$

where

H	building heat transfer coefficient, W/K
Q_{space}	net heating energy need for space heating of a building, kWh
T_i	indoor air temperature, °C
T_o	outdoor air temperature, °C
Δt	length of time period, h
1000	factor for unit change to W

The overall building heat transfer coefficient is dependent on the net heating energy need for space heating in a building. The space heating need of a building is comprised of energy losses from conduction, air leakage and ventilation. We can now consider the total building heat transfer coefficient to be defined by Equation (5.10).

$$H = H_{cond} + H_{leakage} + H_{vent} \tag{5.10}$$

where

H	total building heat transfer coefficient, W/K
H_{cond}	conduction heat transfer coefficient, W/K
$H_{leakage}$	air leakage heat transfer coefficient, W/K
H_{vent}	ventilation heat transfer coefficient, W/K

The conduction heat transfer coefficients are calculated with the Equation (5.11).

$$H_{cond} = H_{wall} + H_{roof} + H_{floor} + H_{window} + H_{door} + H_{coldbridge} \tag{5.11}$$

where

H_{cond}	total conduction heat transfer coefficient, W/K

H_{wall}	wall heat transfer coefficient, W/K
H_{roof}	roof heat transfer coefficient, W/K
H_{floor}	floor heat transfer coefficient, W/K
H_{window}	window heat transfer coefficient, W/K
H_{door}	door heat transfer coefficient, W/K
$H_{coldbridge}$	cold bridge heat transfer coefficient, W/K

The heat transfer coefficient of the walls, roof, floor, windows and doors that are in contact of outdoor air is calculated with the Equation (5.12).

$$H_{part} = \sum U_i A_i \tag{5.12}$$

where

H_{part}	heat transfer coefficient of a specific part, W/K
U_i	thermal transmittance of part i, W/(m^{2}K)
A_i	area of part i, m^2

A cold bridge is caused by material that is placed inside an insulation but that has much higher heat conduction than that of the insulation. Cold bridges cause extra heat loss in a building but may be needed for example to reinforce a structure with steel. The cold bridge heat transfer coefficient is calculated with the Equation (5.13).

$$H_{coldbridge} = \sum l_k \Psi_k \tag{5.13}$$

where

$H_{coldbridge}$	cold bridge heat transfer coefficient, W/K
l_k	length of the line like cold bridge, m
Ψ_k	additional conductance of a line like cold bridge, W/(m K)

The air leakage heat transfer coefficient is calculated with the Equation (5.14).

$$H_{leakage} = \rho_i c_{pi} q_{lp} \tag{5.14}$$

where

$H_{leakage}$	heat loss via air leakage, W/K
ρ_i	air density, 1.2 kg/m^3
c_{pi}	specific heat capacity of air, 1000 J/(kg K)
q_{lp}	air leakage stream, m^3/s

The ventilation heat transfer coefficient is calculated with the Equation (5.15).

$$H_{vent} = \rho_i c_{pi} q_{lp} \tag{5.15}$$

where

$H_{leakage}$	heat loss via air leakage, W/K
ρ_i	air density, 1.2 kg/m^3
c_{pi}	specific heat capacity of air, 1000 J/(kg K)
q_{lp}	ventilation removal air stream, m^3/s

The total heat transfer coefficient of a building is formed by using the Equations (5.9) – (5.15). In real life, the heat transfer coefficients are calculated from the data on the building documents as well as various tables provided in the guidelines of [14].

5.4.2 Building heat gain

Heating systems used for building space heating are sized based on the total building heat transfer coefficient H defined by Equation 5.9. As the building heat transfer that occurs in buildings is dependent on the outdoor temperature, a reference temperature is used for calculating the overall power need for space heating in a building. Currently, the outdoor temperature reference that is used in Finland is based on the geographical location of the building. For this, Finland has been divided in to four temperature regions that are shown in Figure 5.3.

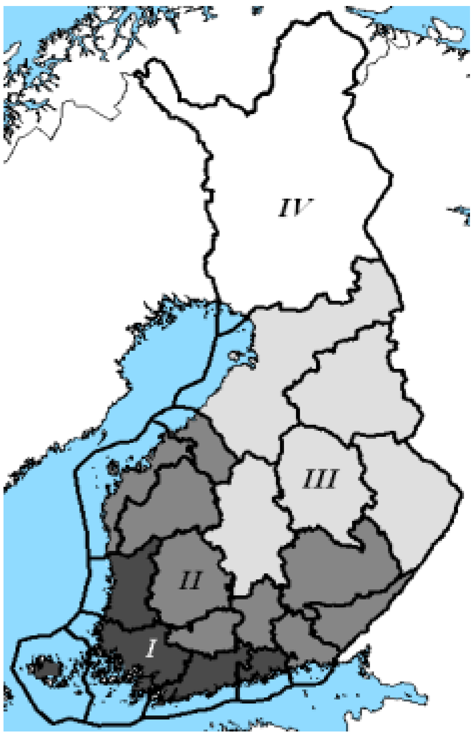

Figure 5.3 *Different temperature regions of Finland [15]*

In Table 5.1 is shown the reference outdoor temperatures and the average outdoor temperature during the heating season of the four temperature regions in Finland.

***Table 5.1** Reference outdoor temperatures and the average outdoor temperatures during heating season of the different temperature regions in Finland [15]*

Temperature region	Reference outdoor temperature	Average outdoor temperature during heating season
I	-26 °C	1 °C
II	-29 °C	0 °C
III	-32 °C	-1 °C
IV	-38 °C	-5 °C

The temperature difference used for calculations is the difference between the reference outdoor temperature of the specific region and an indoor temperature reference, which is typically 21 °C [14]. The power rating of the heating system is then defined as the product of the building heat transfer coefficient and the calculated temperature difference minus the heating power from other heating sources as shown in Equation (5.16) [14].

$$P_{heat} = H(|T_{iref} - T_{oref}|) - P_{misc} \tag{5.16}$$

where

P_{heat}	building heating system power, W
H_{space}	building heat transfer coefficient, W/K
T_{iref}	indoor temperature reference, °C
T_{oref}	outdoor temperature reference, °C
P_{misc}	heating power from other heating sources, W

Buildings can also have other heat sources than the primary heating system. Typically, a fireplace can be used to produce extra heat during the wintertime and thus reducing the needed heating power of the heating system [9].

5.4.3 Building time constant

Defining the heat capacity C for a given building is a more complicated task. The heat capacity affects heats ability to store in the solid structures inside the building and therefore it affects the buildings ability to gain and lose heat. The heat capacity can be calculated if all of the building materials of the building are known. However, the heat capacity can be also defined more generally through what is called the building time constant [14]. The building time constant is defined as:

$$\tau = \frac{C}{H_{space}} \tag{5.17}$$

$$\Rightarrow \; C = \tau H_{space} \tag{5.18}$$

where

τ	building time constant, h
C	building heat capacity, Wh/K
G	building heat transfer coefficient, W/K

The building time constant τ can be used to characterize the temperature change occurring inside the building during the heating season. The building time constant can be calculated using the heat capacity values for different types of buildings provided in [14]. Typically, the building time constant is between 1-7 days [14].

5.4.4 Thermostat parameters

For the thermostat, the thermostat parameters of temperature set value, temperature upper limit and temperature lower limit need to be defined. As it was previously discussed, the thermostat of this model is a simple, binary-operating thermostat. In this model, the temperature set value is chosen arbitrarily and the limits are also chosen arbitrarily and symmetrically around the set value.

5.4.5 Operation of the thermodynamic model

Using the information of the previous segments, a thermodynamic model of the indoor temperature and the operation of a thermostat was done with Matlab. In Figure 5.4 is shown the block diagram of the Matlab model.

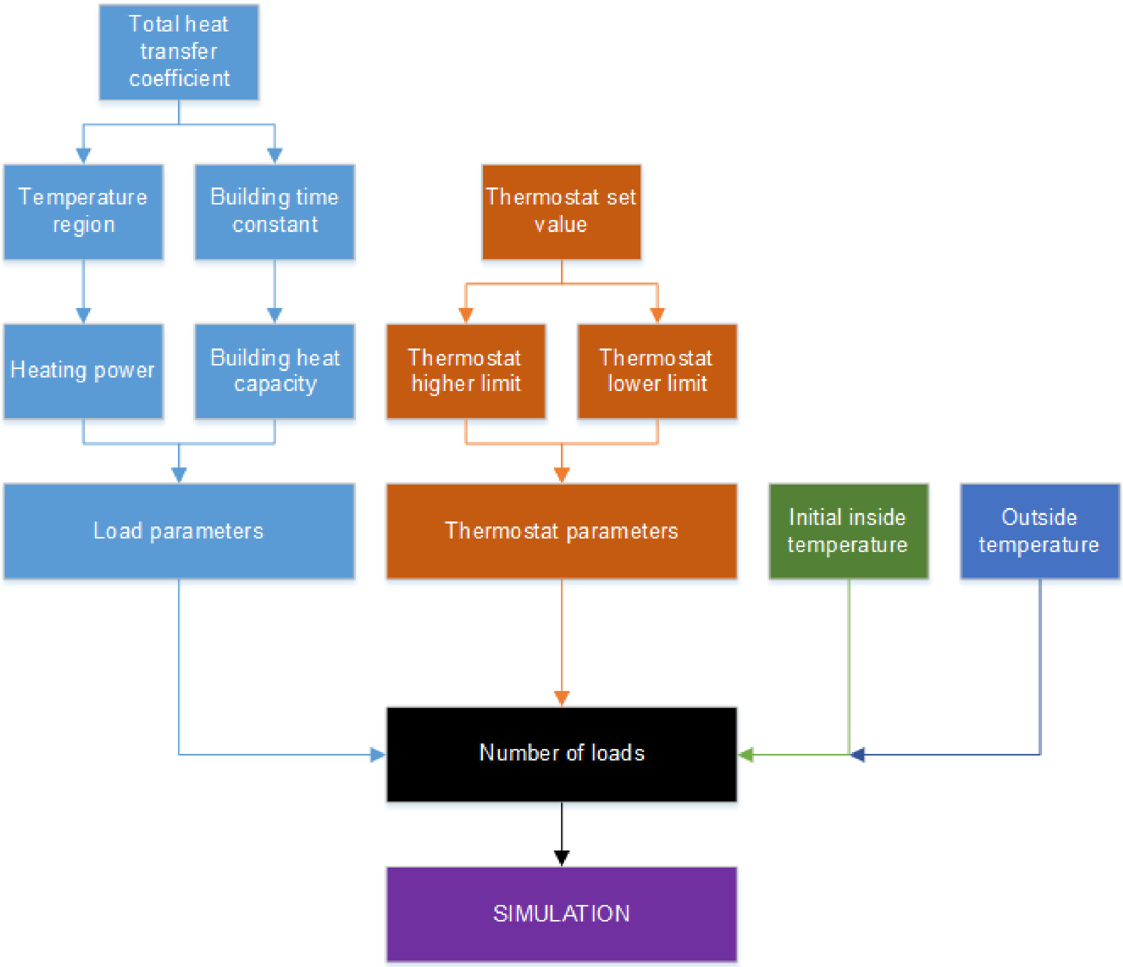

Figure 5.4 *Block diagram of the Matlab model*

The model uses Equation (5.5) to solve the current indoor temperature at each time step. The thermostat settings are then used to turn the heating power on and off. When the building reaches the lower temperature limit of the thermostat, P_{heat} is used to model the heat gain of the building. When the building reaches the higher temperature limit of the thermostat, the heating power is turned off and the value of P_{cool} is used to determine the cooling of the building.

In Figure 5.5 is shown the simulation results of the model using the following parameters:

- Total heat transfer coefficient of the building $H = 150\frac{W}{K}$
- Building time constant $\tau = 2\ d$
- Total heat capacity of the building $C = 25.92\ MJ$
- Power of the heating system $P_{heat} = 5.1\ kW$
- External heating power $P_{cool} = 0$
- Initial indoor temperature $T_i(0) = 21\ °C$
- Outdoor temperature $T_o = -1\ °C$
- Thermostat set temperature for the building $Tset = 20\ °C$
- Thermostat higher temperature limit $Thlim = Tset + 0.5 = 20.5\ °C$
- Thermostat lower temperature limit $Tllim = Tset - 0.5 = 19.5\ °C$
- Simulation time $t = 48\ h$

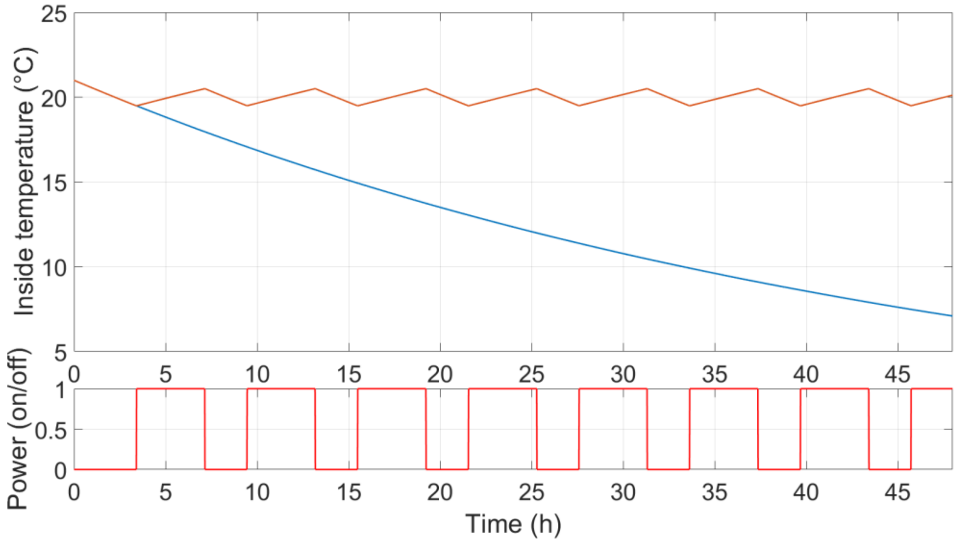

***Figure 5.5** Simulation of indoor temperature and operation of thermostat of a building*

In Figure 5.5 the indoor temperature during normal thermostat operation is shown in orange, the indoor temperature when no heating is used is shown in blue and the on/off states of the heater power is shown in red. The Figure 5.5 is similar to the theoretical operation of the system shown in Figure 5.1. From this reference model of a single building, an aggregated model can be created.

5.5 Aggregated load model of the space heater loads in Finland

The aggregated load model is a tool that allows the simulation of thousands or hundreds of thousands individual loads simultaneously without causing the simulation time to exceed any practical limit. In the case of simulating space heater loads in Finland, an aggregated load model is definitely needed, as the individual loads are small, but there are a lot of them, as was discussed in the section 3.4. To build an aggregated load model, the reference model made in the previous section is used as a base. From this base model, the number of loads that are being simulated can be scaled up by randomly generating values for the parameters of each individual load within specified limits. To aggregate the reference model, following was done:

Load parameters
The total heat transfer coefficient is normally distributed with a chosen mean value and standard deviation. The value of total heat transfer coefficient for each load is then randomly chosen from this normal distribution. The temperature region is randomly chosen from the defined regions. The building time constant is randomly chosen between 1 – 7 for each load. Heating power and building heat capacity is then calculated for each load based on the total heat transfer coefficient, temperature region and building time constant.

Thermostat parameters
The thermostat set value is randomly chosen for each load. The thermostat limits are then chosen symmetrically around the set point.

Temperature parameters
The initial indoor temperature is randomly chosen to be a value between the thermostat limits. The outdoor temperature can be chosen arbitrarily for each load.

The Matlab model then calculates the temperature behavior of each building for every time step of the simulation. The use of heating power is also calculated and plotted as percentage of total heating power available. Using arbitrary parameter values for the model yielded results that are displayed in Figure 5.6 and Figure 5.7. In Figure 5.6 is shown the indoor temperatures as a function of time when 5, 10 and 100 units was simulated. In Figure 5.7 is shown the percentage of heating power that is in use as a function of time when 5, 10 and 100 units was simulated.

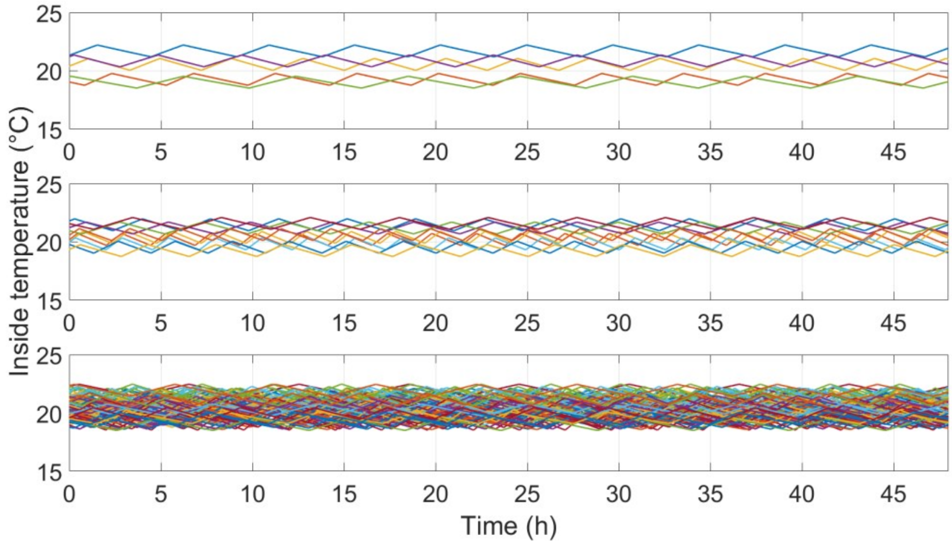

Figure 5.6 *Indoor temperature of buildings using 5 units (top), 10 units (middle) and 100 units (bottom)*

From Figure 5.6 can be seen how the amount of units modeled affects the variance of the indoor temperatures averages. When smaller amounts of units are used for simulations, individual loads have significant effect to the temperature average. When 100 units was used in the simulation, the effect a single unit has on the results is no longer distinguishable. This has a direct correlation to the more interesting parameter of the power usage of the loads, which is displayed in Figure 5.6.

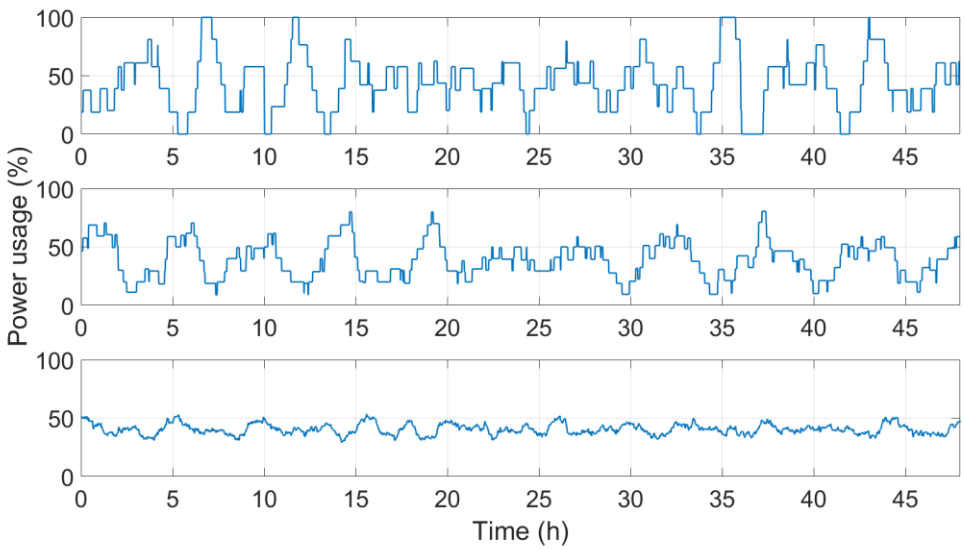

Figure 5.7 *Used heater power compared to total heater power using 5 units (top), 10 units (middle) and 100 units (bottom)*

From Figure 5.7 can be seen that when there are low amount of units being simulated, the total power usage sees a lot of variance, but with 100 units, the power usage is fluctuating around the mean value with a lot less fluctuation. This aggregated electric space heater load can be used for simulations, where these interesting characteristics can be studied in more detailed.

6. SIMULATIONS

In this chapter, simulations regarding the compatibility of electric, thermostat-controlled space heater loads for frequency control is presented. In the simulations, various parameters of the aggregated space heater loads was studied in order to demonstrate their performance as a possible frequency reserve. In the last segment, conclusions of the simulations are given.

6.1 Uncertainty and load forecasting

Using the aggregated load model presented in the previous chapter, three important characteristics of a load control group was studied. These characteristics were the following:

Uncertainty of the power usage of the load control group
For the load control group to be suitable for frequency control, the uncertainties caused by the intermittent power usage of the thermostat-controlled loads needs to be understood in order to understand the available control capacity for up- and down-regulation.

Load forecasting
The power usage of the electrical space heaters is not constant, as the outdoor temperature has a strong correlation to the usage of heating power. For this type of load to be used for frequency control, it is important to understand how easy it is to predict the loads' future power usage.

Behavior of the load control group after the control action
For thermostat-controlled loads, the load control action may cause a lot of unwanted synchronization. In the case of heating loads, this synchronization, also known as cold-load pickup, may cause the power system loading to increase after the load control action. The magnitude of this kind of behavior needs to be known in order to be able to create a properly working frequency reserve using load control.

In the following segments are shown the simulation results regarding these characteristics with a discussion in the last segment.

6.2 Uncertainty of the load control group's power usage

The three major parameters that affects the uncertainties of the power usage of the load control group are the size of the load population, the building time constant of the load control group and the outdoor temperature that the load control group experiences. The effects of these parameters to the uncertainty can be demonstrated with simulations. In these simulations, the following parameters were used:

Heat transfer coefficients of the load control group form a normal distribution with a mean value of 100 W/K and standard deviation of 5 % of mean value. This gives the load control group an average heating power of 5000 kW per unit, which represents a small residential building.

Thermostat set values were randomly selected between 19 – 22 °C and the upper and lower limits were set symmetrically around the set value with a 0.5 °C difference to the set value.

Temperature regions were limited only to regions I and II to represent a load control group that is geographically located close to each other. For each unit, the temperature region is randomly selected from the two.

Using these simulation parameters, the following simulations were done. In Figure 6.1 is shown the power usage of the load control group with different sizes of load populations (building time constant average is one (1) d and outdoor temperature is 0 °C).

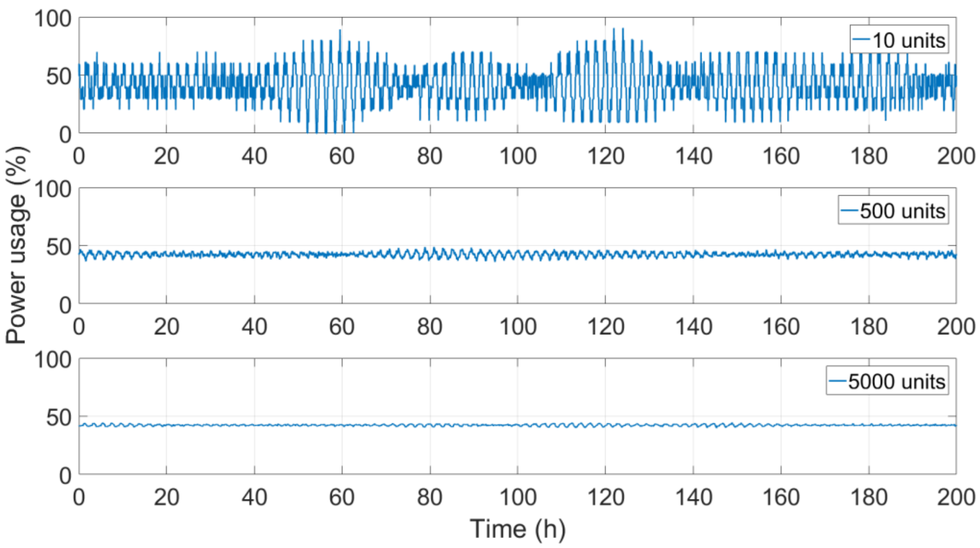

Figure 6.1 *Power usage of the load control group with different sizes of load populations*

From Figure 6.1 can be seen that the synchronization of the load control group decreases significantly when the size of the load population is increased. When only 10 units form the load control group, the power usage sees a lot of fluctuation as it is very likely that most of the loads in the group are on or off simultaneously. This uncertainty is greatly reduced by increasing the amount of loads in the load group and the power usage is much easier to predict. In Figure 6.2 is shown the power usage of the load control group with different values of building time constants (size of the load population is 1000 and outdoor temperature is 0 °C)

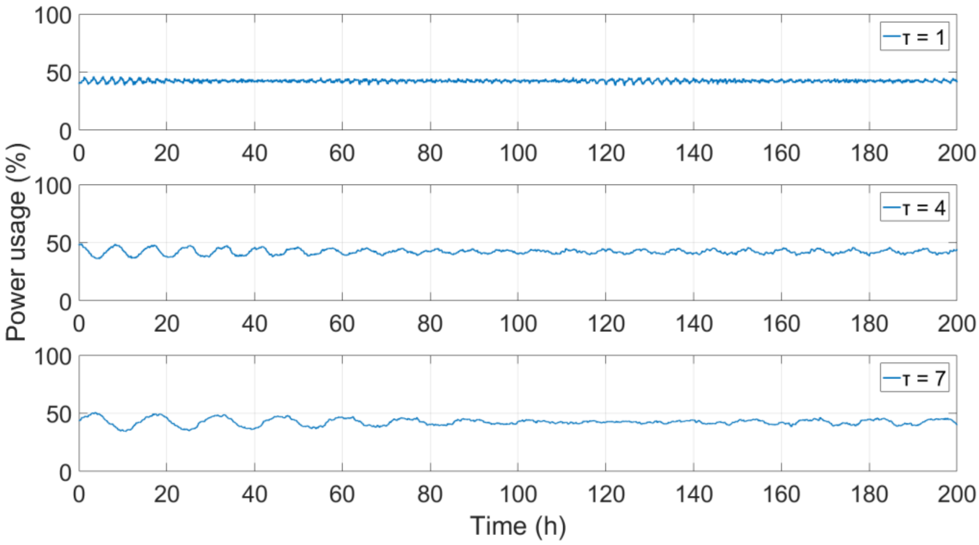

Figure 6.2 *Power usage of the load control group with different values of building time constants*

From Figure 6.2 can be seen that when the overall building time constant of the load control group increases, it causes more synchronization and therefore increases the uncertainty of the power usage. The building time constant affects the on and off time of the thermostat; the higher the building time constant is, the longer it takes the building to cool down and heat up. When the building time constant of the load control group increases, it requires more load units to reach the same levels of predictability. In Figure 6.3 is shown the power usage of the load control group with different outdoor temperatures (size of the load population is 300 and building time constant average is one (1) d).

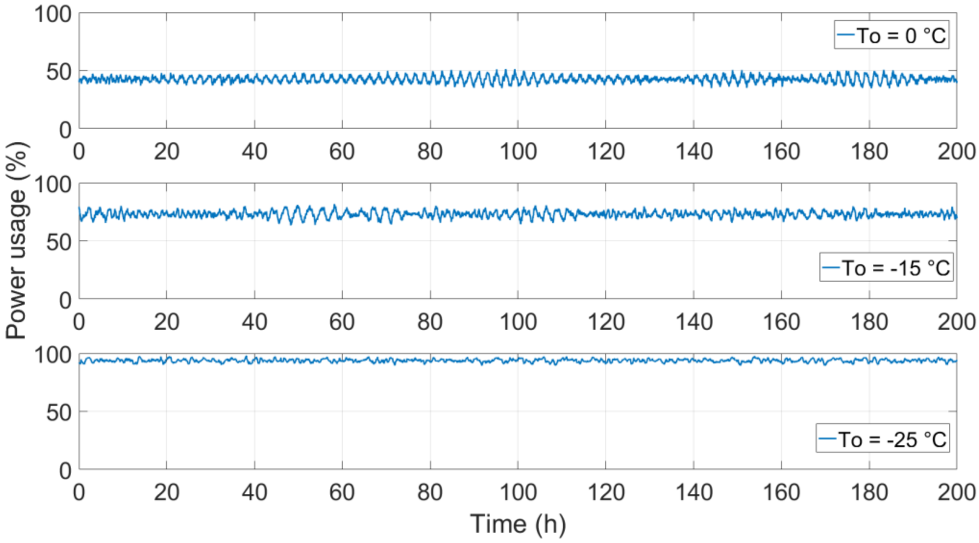

Figure 6.3 *Power usage of the load control group with different* ***outdoor*** *temperatures*

From Figure 6.3 can be seen that when the outdoor temperature decreases, the uncertainty of the power usage also decreases. The outdoor temperature has an opposite effect to the building time constant on the thermostat operation. The lower outdoor temperature causes the building to cool down faster, which in turn causes the overall power usage to increase. When the outdoor temperature decreases, the power usage of the load control group starts to increases, until finally reaching 100 %, when the heating power of the buildings is unable to maintain the thermostat set value. In Table 6.1 is shown the effects of these parameters to the uncertainty of the power usage of the load control group.

Table 6.1 *The size of the load population needed to reach different levels of power usage accuracies with different parameter values*

Parameters	Within of mean value			
	±15%	±10%	±5%	±3%
$\tau = 1\,d$ $T_o = 0\,°C$	500	1600	7000	-
$\tau = 3\,d$ $T_o = 0\,°C$	600	1700	8000	-
$\tau = 7\,d$ $T_o = 0\,°C$	700	1800	9000	-
$\tau = 1\,d$ $T_o = -15\,°C$	250	550	2300	6000
$\tau = 1\,d$ $T_o = -25\,°C$	65	120	450	1100

From Table 6.1 it can be seen that the building time constant has a small negative effect on the predictability of the load control group. In addition, outdoor temperature has a significant effect on the predictability of the load control group as colder outdoor temperatures significantly increase the predictability of the load control group.

6.3 Temperature correlation

The outdoor temperature has a direct correlation to the total power usage percentage of the heating loads. This is because colder outdoor temperature causes the building to lose heat more rapidly, and causes the heating loads to be on more often. The two primary parameters that affect the overall power usage level of the load control group is the outdoor temperature and the temperature region that is used to size the heating system. These effects were studied in the following simulations. In these simulations, the following parameters were used:

Heat transfer coefficients of the load control group form a normal distribution with a mean value of 100 W/K and standard deviation of 5 % of mean value. This gives the load control group an average heating power of 5000 kW per unit, which represents a small residential building.

Thermostat set values were randomly selected between 19 – 22 °C and the upper and lower limits were set symmetrically around the set value with a 0.5 °C difference to the set value.

Load population was set at 5000 units to provide a load control group with less fluctuation of power usage

Building time constant was set randomly between 1 – 3 to each building

In Figure 6.4 is shown a simulation of load control that is fully located in temperature region I in different outdoor temperatures.

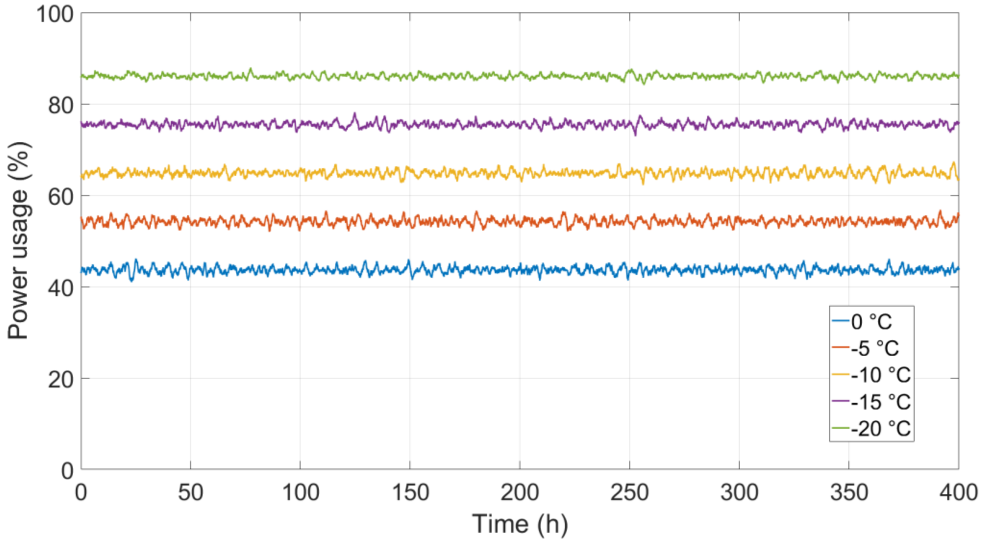

Figure 6.4 *Power usage of the load control group in temperature region I with different outdoor temperatures*

From Figure 6.4 can be seen the effects of different outdoor temperatures on the power usage of the load control group located in entirely in the temperature region I. Lower outdoor temperatures also decreases the load synchronization, as the power usage is approaching towards the upper limit of 100 %, as was discussed in previous section. In Figure 6.5 is shown a simulation of load control groups that are located in different temperature regions when the outdoor temperature is -15 °C.

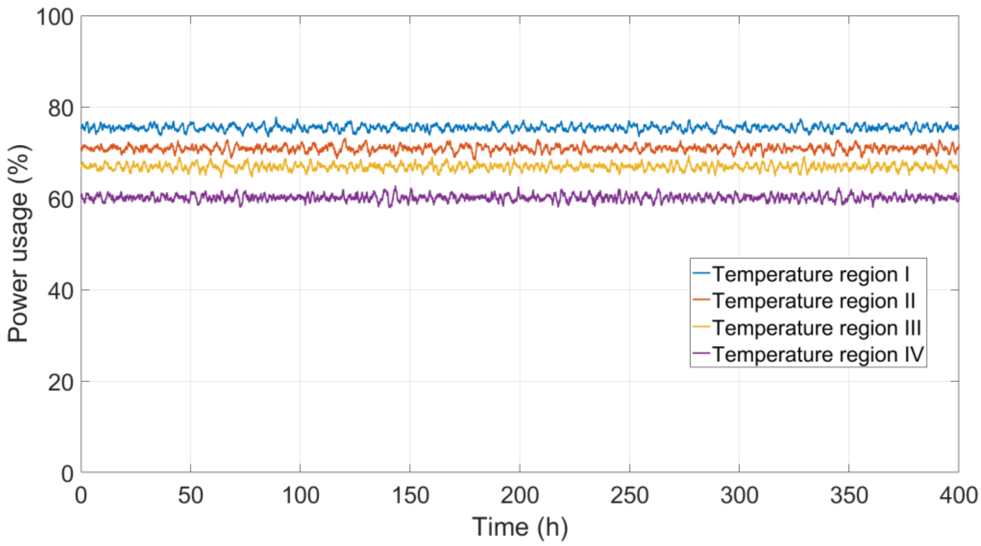

Figure 6.5 *Power usage of the load control group in different temperature regions when outdoor temperature is – 15 °C*

From Figure 6.5 can be seen that the overall power usage level is different for load control groups in different temperature regions. This is because the load control groups that are located in the colder regions have more heating power and need less on time to maintain the same levels of indoor temperatures as units located in warmer areas. In Table 6.2 is presented the power usage levels of different load control groups located in different temperature regions with different outdoor temperatures.

Table 6.2 *Power usage of the load control group located in different temperature regions with different outdoor temperatures.*

Power usage	**Outdoor temperature**				
Temperature region	0 °C	-5 °C	-10 °C	-15 °C	-20 °C
I	44 %	54 %	65 %	75 %	85 %
II	41 %	51 %	61 %	71 %	81 %
III	38 %	48 %	57 %	67 %	76 %
IV	34 %	43 %	52 %	60 %	69 %

From Table 6.2 can be seen the linear correlation that the outdoor temperature has for the power usage of the load control groups. For the different load control groups, the overall power usage increases at the rate of approximately 2 % per 1 °C of change in outdoor temperature. For the different temperature regions, the overall power usage can also be accurately estimated.

6.4 Load control action and regulation capacity

The load control action can have a negative effect on the power usage of the load population, if too many thermostat-controlled loads are being turned off for too long. This can then cause an increase in the over power usage that the power system sees as an effect called cold-load pickup. In the cold-load pickup, increased amount of synchronization occurs when many of the loads in the load control group turn on simultaneously after the control action. This effect can be demonstrated with simulations. In the simulations, following simulation parameters were used:

Heat transfer coefficients of the load control group form a normal distribution with a mean value of 100 W/K and standard deviation of 5 % of mean value. This gives the load control group an average heating power of 5000 kW per unit, which represents a small residential building.

Thermostat set values were randomly selected between 19 – 22 °C and the upper and lower limits were set symmetrically around the set value with a 0.5 °C difference to the set value.

Temperature regions were limited only to regions I and II to represent a load control group that is geographically located close to each other. For each unit, the temperature region is randomly selected from the two.

To test the effect of cold-load pickup, all loads were forced to turn off for a given time simultaneously without allowing them to turn back on even if the indoor temperature would decrease below the lower thermostat limit. In Figure 6.6 is shown the effects of a load control action, where all of the loads are turned off for different amounts of time with 5000 loads (building time constant average two (2) and outdoor temperature 0 °C).

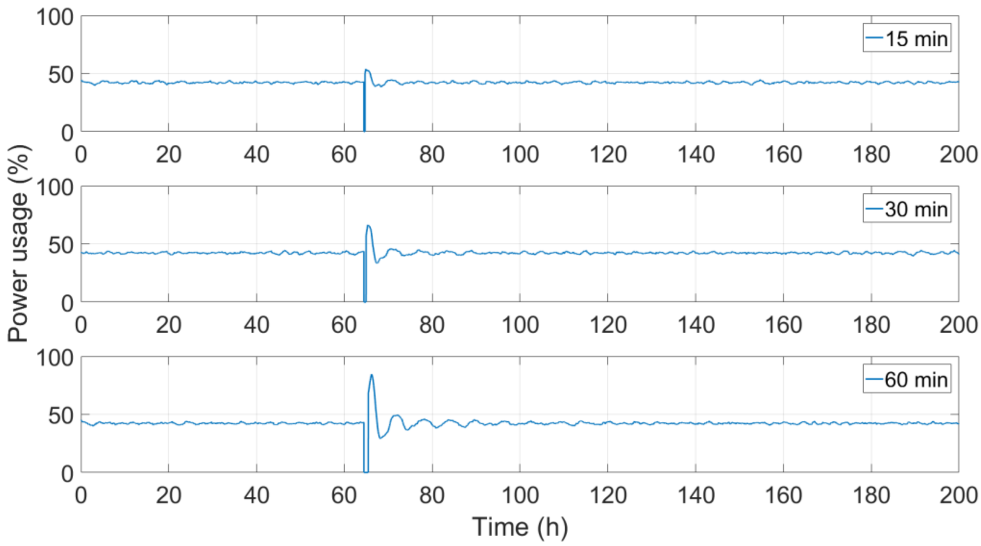

Figure 6.6 *Effects of load control action that turns all of the loads off for different amounts of time with 5000 loads*

From Figure 6.6 can be seen the increase in synchronization after the control action when the load control action takes a longer time. When the load control action lasts for 15 minutes, the power usage after the control action sees a 12% increase. The building indoor temperatures return to normal when the power usage decreases back to the mean value the first time but the power usage sees abnormal fluctuation due to the synchronization of loads for 5 hours. When the load control action lasts for 30 minutes, the power usage sees a 24% increase and the effects of the control action take around 15 hours to clear. When the control action lasts for 60 minutes, the power usage sees a 42% peak and the effects of the load control action takes around 35 hours to clear. For a practical load control solution, these effects for the power system are unacceptable. Therefore, the load control action effectively decreases the real available capacity that is available to be used for up- and down-regulation. To simulate the effects of the load control action for up- and down-regulation capacities, a series of simulations were done. For up-regulation, the reduction in control capacity because of control action can be estimated by calculating the load peak that occurs after the control action, where all load units are turned off simultaneously. The load peak represents the percentage of loads that decreased below the lower thermostat limit and were supposed to turn back on during the load control action. For down-regulation, a similar test can be done by forcing the all of the load units to turn on during the control action and calculating how much the power usage drops after the control action.

The main parameters that affect the control capacity available for the up- and down-regulation are the length of the control action, outdoor temperature and the building time constant of the load control group. The longer the control action is, the less amount of loads can be used for control without causing a negative effect on the user. Higher outdoor temperatures increases the relative capacity (percentage of total power usage) for up-regulation and decreases the relative capacity for down-regulation and vice versa. Higher building time constant makes the load control group less sensitive to the control action and therefore increases the relative capacity for both up- and down regulation. In these simulations, the results show the decrease in up- and down-regulation capacity caused by the control action, if the thermostat limitations are taken into account. If the indoor temperature reaches temperatures outside of the thermostat limitations during the control action, the load is not considered to be able participate in the control action. In Table 6.3 is shown the effects of how different parameters decrease the up-regulation capacity in a control group of 5000 units.

Table 6.3 *Effects of control action length, outdoor temperature and building time constant for decreasing up-regulation capacity of the load control group*

Decrease of up-regulation capacity caused by the control action				
	15 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	15 %	18 %	22 %	25 %
2..3	8 %	11 %	13 %	15 %
3..4	6 %	8 %	11 %	12 %
4..5	5 %	7 %	8 %	10 %
5..6	3.5 %	6 %	7 %	8 %
6..7	3 %	5 %	6 %	7 %
	5 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	4 %	5 %	6.5 %	8 %
2..3	3 %	4.5 %	5 %	5.5 %
3..4	2.5 %	3 %	3.5 %	4.5 %
4..5	2 %	2.5 %	3 %	4 %
5..6	1.5 %	2 %	2.5 %	2 %
6..7	1 %	1.5 %	2 %	1.5 %
	1 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	<1 %	<1 %	1 %	1 %
2..3	<1 %	<1 %	<1 %	1 %
3..4	<1 %	<1 %	<1 %	<1 %
4..5	<1 %	<1 %	<1 %	<1 %
5..6	<1 %	<1 %	<1 %	<1 %
6..7	<1 %	<1 %	<1 %	<1 %

From Table 6.3 can be seen how the lower outdoor temperatures have a significant effect on the up-regulation capacity as the usable capacity is decreased twice as much between outdoor temperatures of 0 °C and -20 °C. On the other hand, a load control group with higher building time constant is a lot less sensitive to the effects of load control. Finally, when the control action is only one minute long, it has a very minimal effect on the load control group regardless of the other parameters. In Table 6.4 is shown the effects of different parameters decrease the down-regulation capacity in a control group of 5000 units.

Table 6.4 *Effects of control action length, outdoor temperature and building time constant for decreasing down-regulation capacity of the load control group*

Decrease of down-regulation capacity caused by the control action				
	15 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	18 %	16 %	11 %	6 %
2..3	11 %	10 %	7 %	5 %
3..4	8 %	7 %	5 %	4 %
4..5	7 %	6 %	4 %	3 %
5..6	6 %	5 %	3 %	2.5 %
6..7	5.5 %	4 %	2 %	1.5 %
	5 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	6 %	5 %	4 %	1.5 %
2..3	4 %	3 %	2.5 %	<1 %
3..4	3 %	2.5 %	<1 %	<1 %
4..5	2.5 %	2 %	<1 %	<1 %
5..6	2 %	<1 %	<1 %	<1 %
6..7	1 %	<1 %	<1 %	<1 %
	1 minute control action			
Building time constant	**Outdoor temperature**			
	0 °C	**-5 °C**	**-15 °C**	**-20 °C**
1..2	<1 %	<1 %	<1 %	<1 %
2..3	<1 %	<1 %	<1 %	<1 %
3..4	<1 %	<1 %	<1 %	<1 %
4..5	<1 %	<1 %	<1 %	<1 %
5..6	<1 %	<1 %	<1 %	<1 %
6..7	<1 %	<1 %	<1 %	<1 %

From Table 6.4 can be seen how the lower outdoor temperature significantly increase the capacity available for the down-regulation as the decrease in capacity is 2 – 3 times less in outdoor temperature of -20 °C compared to 0 °C. Again, the increase in the building time constant causes the capacity to increase as the load control group is less sensitive to the control action. Finally, when the control action length is less than 5 minutes, the capacity is not greatly affected by the control action.

6.5 Discussion

The effects of different parameters for the load control group's uncertainty of power usage was simulated in section 6.2. From these results, it can be concluded that the size of the load population is the critical factor to define the uncertainty of the power usage. Larger building time constants also increase the uncertainty of the power usage of the load control group. Building time constant has a linear correlation to the uncertainty of the power usage; when the average building time constant of the control load group increases by 1 d, the size of the load control group needs to be increased approximately by 30 units to maintain the overall power usage within ±10% of mean value. Additionally, the outdoor temperature had a significant effect on the uncertainty of the power usage. When the outdoor temperature was -25 °C, only approximately 8 % of the size of the load population was needed to maintain the overall power usage within ±10% of mean value. However, the average outdoor temperature during the heating season for different regions (Table 5.1) is much closer to 0 °C so this characteristic is not so significant in practice.

The electric space heater loads that are controlled by using a simple on/off –type thermostat have proportional relationship to outdoor temperature. For a given load control group, it should be simple to define this relationship. From the results of the simulations done in section 6.3, it could be concluded that the overall power usage increases by approximately 2 % per a 1 °C change in outdoor temperature. Additionally, the effects of outdoor temperature to the different temperature regions could be easily defined. As outdoor temperature information is easily available, the load forecasting that can be done for this type of load control group should be relatively accurate.

In section 6.4 the effects of the load control action to the power usage was simulated. In the simulations, the effects of cold-load pickup could be demonstrated. Using a simple load control tests for up- and down-regulation, the effects of length of the load control action, building time constant and outdoor temperature to the available relative control capacity could be estimated. From these results, colder outdoor temperatures causes larger decreases on down-regulation capacity while have lesser effect on down-regulation capacity and vice versa. Increasing the building time constant makes the load control group less sensitive to the control action and improves the control capacities in both cases. The length of the control action has a significant effect on the control capacities; when the control length is < 1 minute, the effects of control action to the available capacity become negligible.

7. CONCLUSIONS

In this master's thesis, an aggregated model of electric, thermostat-controlled space heater loads to be used for a power system frequency control analysis was presented. The model was designed to represent building stock and environment conditions of Finland.

The model was also used for simulations, where the compatibility of space heater loads to be used for frequency control was studied through three main criteria; uncertainty of the load group, load forecasting and behavior of the load control group after the control action. From these results, the suitability of the electric, thermostat-controlled space heater loads for frequency control could be estimated. As the electric space heating is primarily the choice for small residential buildings, the unit size of the heater is small. From this, in order to reach the required minimum capacity of reserve (Table 4.1) for the balancing power market and FCR-D, the load population is going to be relatively large which significantly reduces the uncertainties of the capacity estimation. Furthermore, the building time constant characteristic has a linear correlation to the uncertainties regarding the control capacity, so this relationship should be easy to define for a given load control group. Additionally, as this type of electric load has a strong linear correlation with outdoor temperature, the load forecasting should not be difficult. The outdoor temperature characteristics should be relatively easy to define for a given load control group. Finally, he effects of load control have significant effects on the available control capacity if the length of the control action is long. In frequency control, the length of the control action is typically short, so these negative effects have minimal impact on the control capacity. Therefore, it can be concluded that this load type can be effectively used as a part of frequency control reserves, as long as the load population is large enough, the length of the control action is short and the building time constant and outdoor temperature characteristics are known.

The methodology used in this thesis to develop the aggregated load model can be expanded to other thermostat-controlled loads or other loads that have a similar behavior. As these types of loads exist in residential buildings (e.g. fridges, freezers, water boilers, HVAC) it would be a logical next step to expand the model to contain these loads as well. Furthermore, the same principles do apply to larger scale industrial applications (e.g. cold rooms, various intermittent pump loads, supermarkets) as well. In addition, in order to get a better understanding of the behavior and control possibilities of different load types, the various control methods and technologies should be discussed and simulated.

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