Ganesh Neupane

Demand Response Potential of Electrical Space Heating

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Thesis supervisor:

Prof. Matti Lehtonen

Aalto University
School of Electrical
Engineering

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SCHOOL OF ELECTRICAL ENGINEERING Abstract of the Master's Thesis

Author: Ganesh Neupane

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Abstract

Penetration of renewable energy such as wind and solar has been increasing rapidly in the grid. Due to intermittent properties of these sources, power generation cannot be scheduled as well as predicted easily. A sunny day can result in power variation from solar energy than predicted. Similarly, power generated from the wind power have different profile every day and can change in quick time. So excess generation from these renewable sources may result in over frequency problem in the network. Thus it has increased the necessity of frequency control reserves which can be activated instantaneously for stability of power network.

This thesis deals with the potential of using heating energy required for house via electric space heater as frequency responsive reserves during excess generation from renewables. Daily heat loss from a house is calculated on hourly basis with respect to external temperature. Electric space heater stores the equivalent amount of heating energy to compensate loss during the off peak period when price of electricity is cheap. During excess generation from renewables, off peak storing of required heating energy is altered to instantaneous feeding to act as frequency reserves.

Keywords: Renewable Energy, Over frequency, Frequency responsive load, Instantaneous Heating.

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Ganesh Neupane

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LIST OF SYMBOLS AND ABBERVIATION

AGC	Automatic Generation Control
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DSM	Demand Side Management
EM	Electrical Machine
EU	European Union
FW	Flywheel
GW	Giga Watt
PE	Power Electronic System
PV	Photo Voltaic
SMES	Super Conducting Magnetic Energy Storage
TWh	Terawatt-hour
U	Coefficient of Thermal Conductivity
UCTE	Union for the Coordination of Transmission for Electricity
WHO	World Health Organization
J_{FW}	Flywheel resultant inertia
ω_{FW}	Flywheel angular speed
P_{FW}	Power Stored in Flywheel
P_G	Wind Turbine Power
P_{Gav}	Wind Turbine average power
Q_f	Fabric Heat Loss
Q_v	Heat Loss through Ventilation
ΔT	Difference in internal and external temperature
K	Kelvin
°C	Degree Celsius
R	Thermal Resistance

CHAPTER 1

Introduction

1.1 Background

Electricity has become vital element in economic development. Technical progress, industrialization, and the need for the modern comfort have increased its importance. Increased production in electricity translates into a better quality of life and the creation of wealth. Electricity demand is the result of the customer needs and depends upon season, type of day, time of day, and other factors such as weather and country specific factors [1]. The energy production concept was primarily based on demand basis: if there is a demand for more power, utility company would simply increase its generating capacities to meet the essential demand. Power has been vital part of our life, so this has added pressure on the utility company to look out for every possible means of energy production.

The required electricity has been produced from various means ranging from nonrenewable resources such as fossil fuel, nuclear reactor to renewable sources such as the sun, the water and the wind. Electricity production process involves extensive and expensive procedure, thus each unit is associated with certain cost. Along with that the world attention has significantly focused on the issue related to the environment. Global warming and climate change have resulted in substantial increase in the demand for the renewable technology. Several renewable sources such as the wind, sunlight and water have been identified and corresponding technologies are expanding for each source. Renewable energy has high cost of production and installation. Nevertheless, it has been highly appreciated as they tend to directly reduce the pollution. Government authorities have started to take positive actions for the promotion of renewable energy and formulating policies to encourage their usage. Penetration of renewable energy such as wind and solar has been increasing rapidly in the grid. These sources generate electricity throughout the year without creating any adverse effect on the environment.

Renewable sources such as the wind and the sun have positive benefits from an environmental point of a view. However, these resources are characterized by a variable output impacting grid stability and security of system [2]. The fundamental issue in the operation and control of electric power systems is to maintain the balance between generation and demand. Due to the intermittent properties of renewable sources, power generation cannot be scheduled as well as predicted easily. A sunny day can result in power variation from solar energy than predicted. Similarly, the power generated from the wind power has different profile every day and can change in quick time. Such scenario can have adverse effect on the power system stability and may lead to over frequency problem in the grid. Thus it has increased the necessity of frequency control reserves which can be activated instantaneously for stability of power network.

Traditionally, spinning reserve has been supplied from the generators during system emergency and load has been underutilized [2]. System operator uses automatic and manual control mechanisms to match the supply according to variation in demand [3]. Demand can play active role in control of power system balance. Electric loads can actually be turned on or off in response to frequency deviation observed in the power system. Installing a frequency sensor and appropriate control intelligence, loads can respond autonomously to frequency variation and provide fast reserve to the system [4].

1.2 Aim of the work

The overall aim of the work was to study the demand response potential of utilizing heating energy via electric space heater to compensate the heat loss from a house to act as a frequency reserve. Heat loss from the house according to external temperature is calculated. So, with the obtained load profile, potential of using it as a frequency reserve during excess generation is studied.

CHAPTER 2

2.1 Power System Stability

A synchronous electrical power system consists of:

a. Network that connects
b. Synchronous generators
c. Demand.

The network can further be divided into transmission network and distribution network. Power produced from large generators is transmitted via transmission networks. The distribution network is used to transmit power to consumers at lower voltage levels. Synchronous machines maintain synchronization with one another through restoring forces. These forces act whenever synchronized machine tends to accelerate or decelerate with respect to other machines. Hence, synchronous machines can detect and react to a frequency change events on the system automatically. Generators also have governors that detect and react to frequency changes [5].

Electricity demand in a power system varies continuously; hence ideally supply should exactly match and balance in real time. Any aberration of the balance reflects as a fluctuation of system frequency from its nominal value. Furthermore, due to the unavailability and unviability of large storage infrastructure, the balancing procedure has to be done in real time. Balancing is done by adjusting mechanical power input to the prime mover of generator. The procedure takes some time to adjust the generated power due to the steps to be taken while changing the mechanical power [6]. System operator uses automatic and manual control mechanisms to match the supply according to the variation in demand. Moreover, deregulated power systems use commercial arrangements to procure and dispatch technical services to control frequency and voltage, thus ensuring stability of the power system [6].

Frequency is controlled by three control loops in a power system. The Union for the Coordination of Transmission of Electricity (UCTE) of European Transmission System Operator has classified them as Primary, Secondary, and

Tertiary Regulation [3]. These regulation schemes have different operating time scales.

Governors are used for primary regulation [6]. Automatic Generation Control (AGC) performs secondary regulation by automatically adjusting the power output electric generators within control area [6]. Accordingly, tertiary control changes the output of generators such that the contributing secondary regulation will be ready to regulate subsequent load mismatch [6].These regulation schemes can include one or more control subsystem(s) such as the load frequency control, the economic dispatch control, the environment dispatch control, and the security dispatch control [6]. Figure 1 shows the activation of primary, secondary, and tertiary control during frequency deviation.

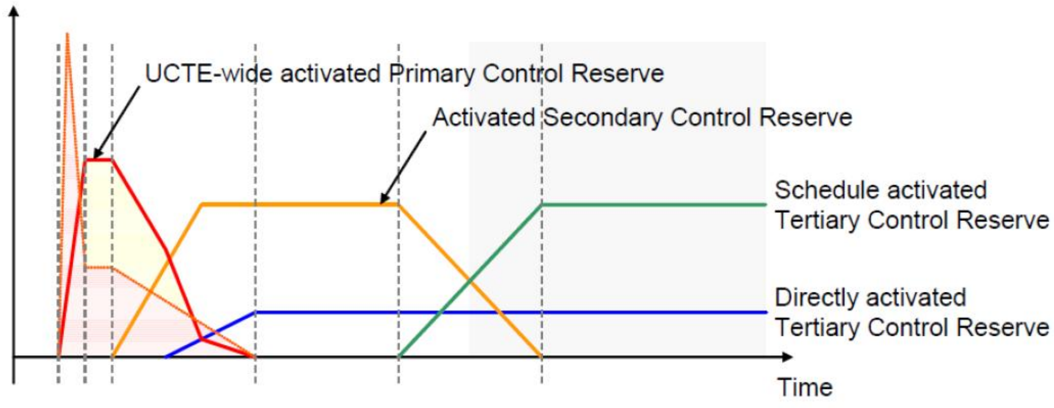


Figure 1 : Operation of Primary, secondary and tertiary regulation [2].

2.2 Load Management

Load management is the deliberate control or influencing of customer load in order to shift the time and use of electric power and energy [7]. Load management concepts are used to reduce the average cost of electricity, improve load factor, and reduce the need for generation capacity by shifting electricity use from peak to off- peak periods. Furthermore, Load Management can improve system efficiency by reducing the share of electric energy generated from relatively inefficient units [7]. Load Management includes a set of objectives designed to control and modify the pattern of demand over various customer of a power utility. The control and modification allows the utility system to meet the energy demand at all times [8]. Load management can be applied to all loads such as industrial load, cooling load, heating load, and lightening load.

Load management was first introduced in the 70's with an aim to reduce the operating cost while maintaining the reliability of the electric power network [9]. Traditionally, the electric power system has been designed to respond to the instantaneous demand of customer for electric power and loads had been uncontrolled. This resulted in large peaks and valleys in power demand which had to be incorporated by the generating unit. Energy storage system using large pumped hydro plants were added by utility companies with an aim of reducing large swings at the primary generating plants. However, the other part of the power system has to respond to the swings in demand thus affecting stability of the overall system.

Load management basically operates at the customer end to control the power demand. This operation may be initiated by either or both of utility company and the customer. It is useful because of the potential to conserve energy and capital in both the production and the distribution of the electric power. It helps the power system engineer to economize the system operation by making the best use of its available generation capacity.

2.2 Some basic Terminology

2.2.1 Connected load

It is the rating (in kW) of the all the energy consuming equipment installed on the consumer premises.

2.2.2 Maximum load demand

It refers to the maximum load, which a consumer can use at any instant of time.

The ratio of the maximum demand and connected load is called Demand Factor and is expressed as:

$$Demand\ Factor = \frac{Maximum\ demand}{Connected\ load}$$

Daily load curve of the consumer is obtained by plotting the load demand of the consumer against the time in hours of a day. Similarly, weekly, monthly, and annual load curves can be presented. The ratio of average load to the maximum load is called load factor and is given as:

$$Load\ Factor = \frac{Average\ load}{Maximum\ load}$$

A load factor of unity implies that the average load and the maximum load are equal, resulting in the constant load curve throughout day. Lower values of load factor indicate the occurrence of the peak value in the load curve. Annual load curve provides information about the time of the year they need for effective load management technique.

2.3 Methods of Implementation

2.3.1 Direct load control

In this method, the utility company directly controls some specific consumer load during the peak hours. The operation of controllable load is postponed during the peak period or in case of emergencies. Loads such as space heater, water heaters, air conditioners, and swimming pool pumps are the prime candidates for the direct load control. Instant control of load may cause discomfort to the consumer. However customers can be offered economic incentives through time dependent price rates of electricity to compensate for the inconvenience [7].

2.3.2 Interruptible Load Tariffs

In this method, consumer is encouraged to change their energy consumption pattern by providing incentive rates. Consumer has to interrupt or reduce the power demand during the peak hours and in the emergency conditions [8]. This requires active involvement of the consumer. Industrial consumer can take the advantage of such tariffs by operating at off- peak periods when the tariff would be low compared to the peak period. Interruptible load tariffs mainly aim to reduce the consumer demands during the peak periods by shifting the use of electrical equipment to off-peak period [7].

2.3.3 Time of Use Tariffs

It is based on the peak load pricing theory. The price of electricity is high during the peak period and lower during the off peak period. It can be considered as an involuntary way for the consumers to adjust the usage of electricity in different times considering the difference in price at that time. Thus, it motivates the consumer to shift their consumption from expensive peak periods to inexpensive off peak period [8].

2.3.4 Thermal Storage:

The main objectives of load management using thermal storage is to store heat to space and water heating during the off-peak periods and use the stored heat during the peak period. It requires the installation of thermal energy storage at the consumer side which can be controlled by both the consumer and the utility [8].

2.3.5 Distribution system loss Reduction:

This is one of the concepts used by the utility company to decrease their operational cost. Utility company benefits financially with the released system capacity. Thus, released system capacity delays a costly expansion and reduces the aging of components [8]. Industrial sector is accountable for large losses compared to other consumers. Thus, the utility company is focusing to save energy by minimizing losses occurring in industries. Similarly, industries are also trying to minimize the loss to reduce the cost of energy consumption [8]. Capacitor installment, voltage modification, and transformer load monitoring are some of the methods being implemented to reduce the distribution system loss.

2.4 Techniques of load Management

2.4.1 Peak Clipping:

Peak clipping focus on decrement of load during the peak periods to get the load profile suitable for the utility. Shortage of energy during the peak period forces utility company to reduce the voltage in the consumer to directly control the load during the peak hours [8]. The shape of load profile obtained with the application of peak clipping technique is shown in Figure 2.

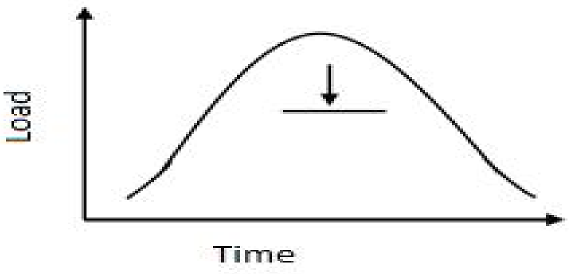


Figure 2: Peak clipping [8].

Peak clipping control is used to reduce capacity requirements, operating costs, and dependence on critical fuel. This direct load control technique is suitable for utility company which does not have enough generating capabilities during the peak hours.

2.4.2 Valley Filling:

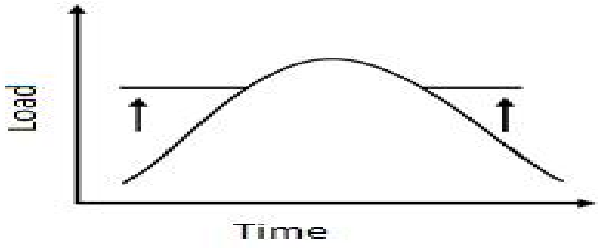


Figure 3: Valley filling [8].

The shape of the load profile obtained with the valley filling technique is as shown in Figure 3.With the aid of the valley filling technique the load is built up during the off-peak periods. Addition of load at the right price will help to reduce the average cost of electricity to all consumers as well as the load factors of the power plant [8].

2.4.3 Load Shifting:

In this technique the peak loads are shifted to off peak time periods. Load is shifted in such a way that it does not change the overall consumption by the consumer. It includes both the advantages of peak clipping and valley filling by moving existing loads from on-peak hours to off peak hours [8].

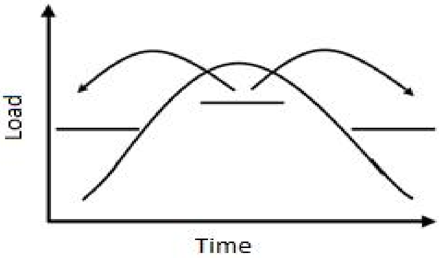


Figure 4: Load shifting [8].

2.5 Penetration of Renewable Energy

The penetration of decentralized and renewable energy resources in the power system is expected to increase considerably in the near future. Renewable energy accounted for one quarter of global power capacity [10]. Figure 5 shows the growth of renewable energy in the share of global electricity production from the year 1998 to 2010.

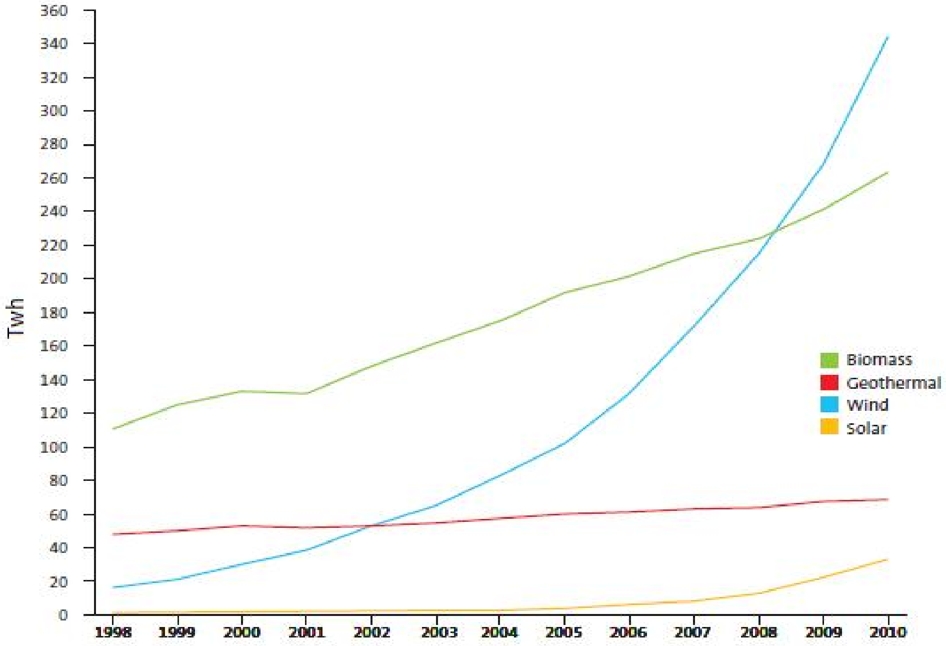


Figure 5: Renewable source electricity production excluding hydraulic (TWh) [11].

The share of hydropower and renewable energy is 312 GW in electricity production which is an increase of 25% compared with the year 2009 [10]. Respectively, global wind power capacity and solar PV capacity increased by approximately 30 GW and 17 GW during the year 2010 [10].

In the European Union, renewables accounted for an estimated 41% of newly installed electric capacity in 2010 [10]. PV accounted for more than half of the total share. The share of electricity from renewable energy in the EU was approximately 20% of total electricity produced in 2009 (42% composed of non-hydropower) [10].

The dependency on renewable energy is continuously growing as their prices continue to fall; consequently share of global electricity production from renewable energy continues to grow.

European Commission has set following targets for 2020 in Climate Change and Energy [12].

a. Lower the greenhouse gas emissions by 20%
b. Generate 20% of energy from renewables
c. Increase 20 % in Energy Efficiency.

Germany, leads the vision with almost 20 % of electricity generation from renewables till the end of 2011 [13]. About 5000 MW of wind power is currently installed in the Nordic grid [14]. Figure 6 shows the amount of registered wind power installed till 2009 and estimated goal for 2020.

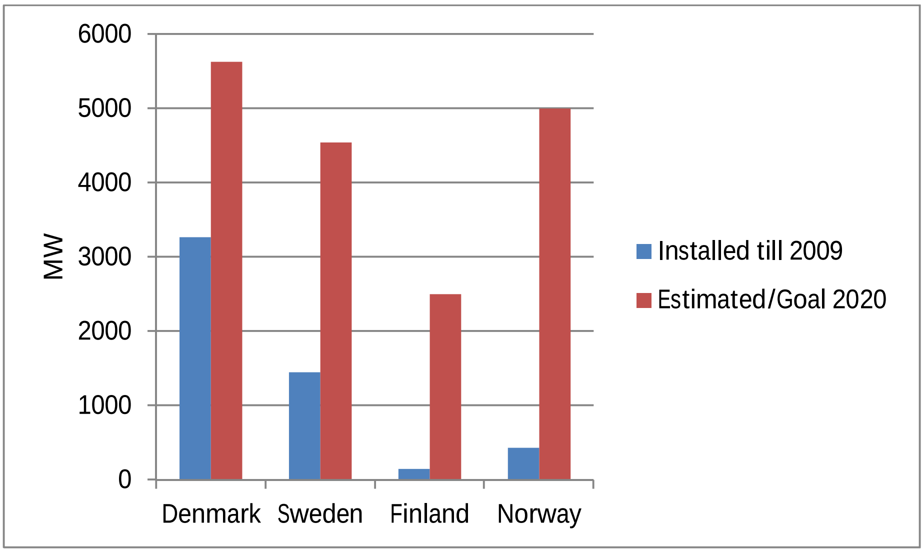


Figure 6: Wind power installed till 2009 and estimation for 2020 in Nordic countries [14].

Wind power generation in the Nordic countries is expected to increase in coming decades as shown in Figure 6. Finland has set a target of 2500 MW by 2020. Similarly, Sweden has targeted 4550 MW from wind power 2020. The total amount of wind power capacity can be estimated to increase up to 15-20 GW by 2020 [14]. Wind power and solar power precede the other renewable energy in terms of penetration in the power system [10]. Wind power is expected to grow rapidly, with Germany alone intending to increase the wind capacity to 45,750 MW in 2020 [15]. Figure 9 shows the growth of world wind capacity from the year 1996 to 2010.

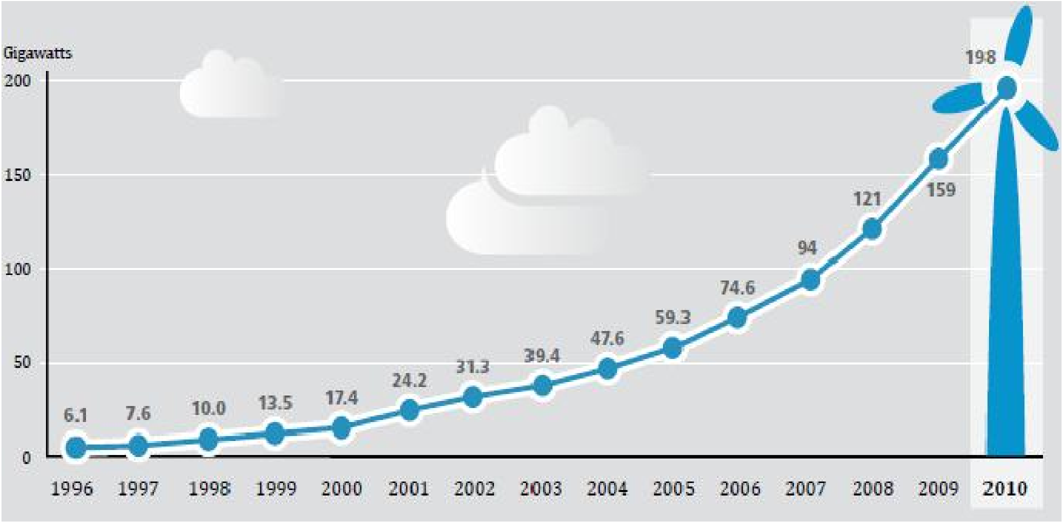


Figure 7: World wind capacity from the year 1996 to 2010 [10].

The wind power capacity reached 198 GW during the year 2010 which is an increment of approximately 24% compared to 2009. EU installed approximately 9.5 GW of wind power in 2010 [10]. Hence total installed capacity reached to 84 GW.

Total existing wind power capacity in the end of 2010 was enough to meet an estimated 2–2.5% of global electricity consumption [10]. Existing wind capacity installed in the EU by the end of 2010 met 5.3% of the region’s electricity consumption.

Solar Photovoltaic energy also observed an increment throughout the globe with an estimated 17 GW of PV capacity added in the year 2010 [15]. PV capacity across the world reached approximately to 40 GW at the end of 2010 [10]. Figure 8 shows the growth of PV capacity from the year 1996 to 2010 [12].

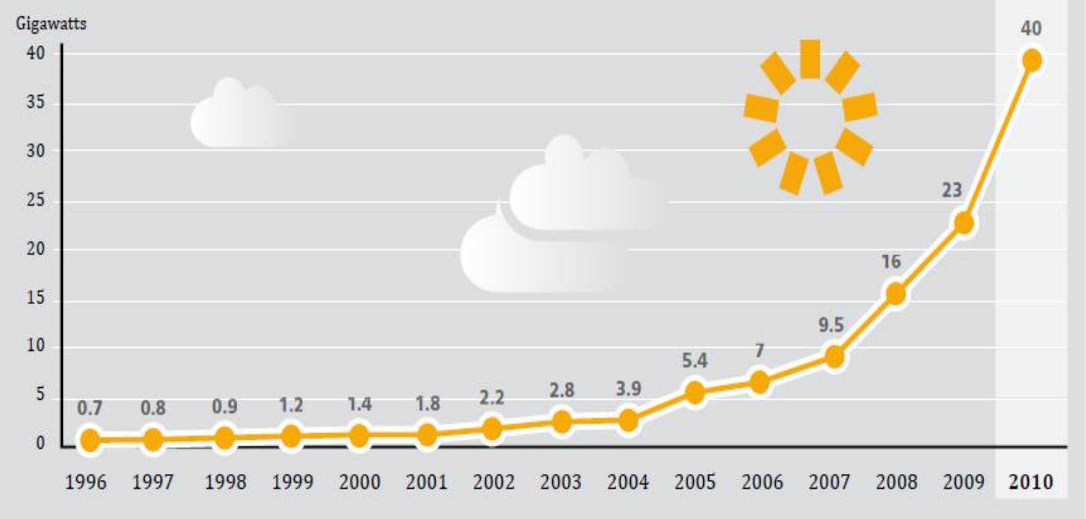


Figure 8: Solar PV, existing world capacity, 1995-2010 [12]

The European Union dominated the global PV market occupying 80% approximately of the total installation of 13.2GW. During the first quarter of 2011, Germany generated 2.75 TWh of electricity with PV, an increase of 87% over the same period in 2010 [10].

The share of electricity from the renewable sources is growing exponentially in recent years. Moreover, environmental pressure and increasing fuel price seems to push countries to install renewable energy. This is expected to increase in the future as the support for production of renewable energy has been put as the national targets and policies. It is foreseeable that renewable energy will predominantly occupy a major share in the final energy production. It also benefits from environmental point of a view however these renewable resources are characterized by a variable output impacting grid stability and security of system.

CHAPTER 3

3.1 Effect on Frequency of power system with large penetration of renewable energy

In recent years, energy systems both in the developed and the emerging economies are undergoing rapid changes due to the emphasis on renewable resources at the policy level and the demand response. This is leading to an intense transition from the current centralized infrastructure towards the massive introduction of distributed generation, responsive and controllable demand and active network management throughout the system. Unlike the conventional generation methods, the output from the renewable sources do not follow the traditional generation/load correlation and they have strong dependencies on environmental conditions. Thus induced condition from a system perspective is posing new challenges associated with the monitoring and controlling demand-supply balance.

High penetration of renewables considerably affects the frequency stability of power system since the wind and the solar photovoltaic generation has neither inertia nor primary frequency response. The variability and uncertainty that is inherent in renewable generation technologies adds the variability and uncertainty in the existing system and can have considerable effects on operations [2]. Variability is the expected change in generation and demand balance .Uncertainty is the unexpected change in generation and demand balance from what was anticipated [2]. Intermittent and variable output renewable energy sources such as wind farms will contribute larger random fluctuations to the load/generation balance as their relative size increases [16]. When, the total supply of energy is different than the total demand, system operators must start operating reserves to correct the energy imbalance. At any instant if the demand exceeds supply, the system frequency falls. Conversely, frequency rises if the power supply exceeds demand. For an example, Germany PV had a system with a capacity of more than 19 GW at the end of June 2011 which accounts for 3.5% of energy from renewables was connected to the grid [17]. Maintaining power system stability has become increasingly difficult for operators. Power generators connected to low voltage grid including PV systems were required to disconnect from the public grid as soon as the grid frequency exceeded 50.2 Hz [17]. Studies have shown that in Germany, 9 GW of solar capacity have to be disconnected when the system frequency reaches 50.2 Hz [17]. Similarly, power system with significant amount of wind power is experiencing problems for balancing the power fluctuation caused by regional wind speed fluctuations [18, 19, 20].

Thus induced variability and uncertainty on system because of the penetration of renewables where output power may increase or decrease unexpectedly have led to the importance of both upward and downward frequency reserves.

3.2 Demand Side Management (DSM)

Demand Side Management (DSM) commonly refers to programs implemented by the utility companies to control the energy consumption at the customer side of the meter [21]. DSM is employed to use the available energy more efficiently without installing new generation and transmission infrastructure. Figure 9 shows the concept of DSM integration of energy Efficiency, Energy Conservation and Demand Response.

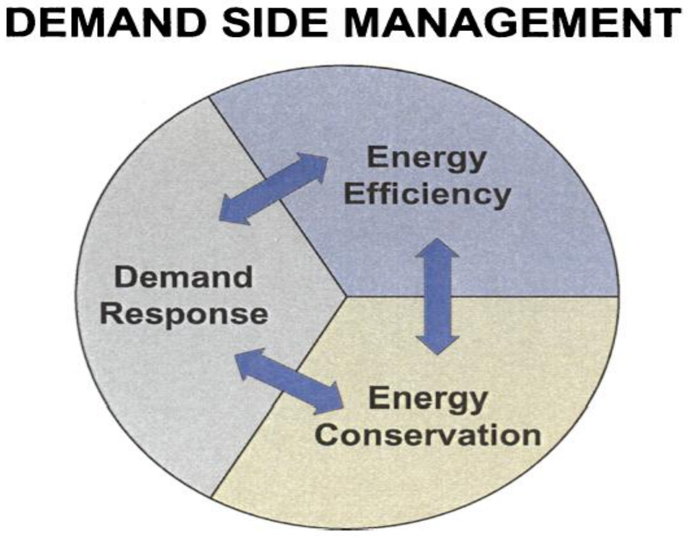


Figure 9: Demand Side management Concept Integration [21].

DSM can be categorized as follows depending on the timing and the impact of the applied measures on the customer process [21].

3.2.1 Energy Efficiency

It refers to the permanent installation of energy efficient technologies for the reduction of energy losses in existing systems. The main aim of energy efficiency is to maintain a comparable level of service with the reduction in energy usage [22]. Examples of energy efficiency are:

- Replacing incandescent light bulbs with compact fluorescent bulbs
- Use of automatic thermostats
- Promotion of home automation devices

3.2.2 Energy Conservation

It deals with making a behavioral choice or change in consumer. The change may last for a short time instant or may be incorporated into a habit of lifestyle [22]. Examples of energy conservation are:

- Lowering thermostat temperature by certain degree to reduce energy consumption during winter
- Opening window in summer instead of using air conditioner.
- Shutting off electrical appliances such as television, computer when they are not in use.

3.2.3 Demand Response (DR).

Demand Response is related to electricity market and price signals. Customer connects or disconnect load in response to a signal from a service provider. These are different from conservation because the activity in terms of energy consumption is not necessarily reduced, rather shifted to another time period. DR initiatives often include information and communication technologies such as Advance Metering Infrastructure (AMI), to maximize the user's awareness of his energy consumption and the related cost in a time basis [22]. DR does not necessarily reduce energy consumption, only consumption patterns are influenced.

Theoretically, the generation and demand can contribute equally to the frequency control as reserves. However, demand response is the most underutilized reliability resource in power system. Power system was controlled with the services from large power plant. Hence, it was a complex procedure to monitor the real time operation of distributed small sized loads. Historic demand response programs have focused on reducing overall electricity consumption and shaving peaks but have not been typically used for immediate reliability response [23].

More recently demand response is being explored and used in reliability services of the power system. These all have been possible due to advances in communication technology and controls. Moreover, with the preconceptions concerning load response capabilities and misunderstandings of power system physical reliability needs, use of responsive load is limited. [23].

3.3 Frequency Responsive loads.

Supply and demand must always be balance in power system real time. Reserves from generation side, including extra capacity of online generators, back up generation are used by system operators to maintain the power system at balanced condition. If the power system stability was difficult to maintain after application of all available reserves, power system operator either shedded the load or trip the generating units as a last measure of action to maintain frequency within acceptance level [23].

Demand can play active role in power system balance control. Electric loads can actually be turn on or off in response to frequency deviation observed in the power system. Installing a frequency sensor and appropriate control intelligence, loads can respond autonomously to frequency variation and provide fast reserve to the system [4]. Household appliances including electric heating, refrigerators, freezers, and water heaters are ideal candidates due to their considerable volume and the possibility of instantaneous control [4].

Researchers have studied using demand as frequency responsive reserves. In the past, utility company had been utilizing load management program [24]. A market-based demand management program using low frequency relay to control industrial loads is studied in [25]. A similar program is implemented in New Zealand power system [24]. In Finland, 1000-MW demands from wood processing, chemical, and metal industry are used as frequency controlled as well as manual reserves [26]. Studies have been mainly preformed on larger industrial loads. A pilot project using the Comfort Choice Technology for controlling air conditioners to provide reserve was carried out by the Long Island Power Authority in 2003 [27].The study done by Pacific Northwest National Laboratory (PNNL) also has suggested that individual household appliances such as refrigerators and air conditioners are suitable for temporary disconnection and can provide fast reserve within seconds [28].Similarly, application of electric heater to manage frequency disturbances has been presented in [28].

3.4 Spinning Reserves from Frequency Responsive Loads

Spinning reserve has been traditionally supplied from the generators which play important function during system emergency. They are called upon in the event of a genuine system emergency such as loss of transmission line or short coming of generated power. Using load to supply spinning reserve would provide another source of revenue, increases reliability of the power system. Moreover it decreases the energy bills of the customer because reserve generation would be freed up to supply energy. As mentioned in Section 2.9, potentially different types of loads can supply contingency reserves to the power system but they should exhibit following characteristics [27].

3.4.1 Storage

It is difficult to store power or energy directly. So, any load that has some storage in its operation process or if some energy can be injected to it,then it can be a good candidate to supply reserves. Thermal storage loads such as building heating/cooling, water heating, refrigeration and compressed air, water pumping are best examples of load that can serve as spinning reserves [27].

3.4.2 Control Capability

The responsive load must be controllable such that it is able to respond to curtailment requests from the utility company [27].

3.4.3 Notification Requirements

Power system contingency should be diagnosed as soon as possible. Thus, load that requires short notification time are best suited for contingency reserves. Thermal loads, water pumping, air compression can be used as contingency reserves because these process generally do not require advance notification curtailment [27].

3.4.4 Response Speed

The load used as contingency reserve must accomplish the given task as soon as it has been notified, without wasting anytime. Studies have shown that load response can exceed generator response. Thermal loads can provide full response instantaneously [27].

3.4.5 Size

The size of each responsive load is small. However, the aggregate size needs to be large enough to be useful. Aggregate size is a very important index to offer more reliability resource for spinning reserve [27].

3.4.6 Minimal Cost

When responsive load is used as the spinning reserve provider, saving is made in the investment to build the generator and transmission devices. Moreover, controller and communication device needs to be installed at the load side. When responsive load work as spinning reserve provider, the price compensation for customer is also considered [27].

Frequency responsive loads are typically smaller than individual generator and they provide statistical rather than a deterministic resources. Moreover, their participation depends upon customer acceptance. Variation in hourly price of energy and associated services makes it economically unviable for customer allowing their loads to participate in providing reserves. Similarly, in some situation because of lack of flexibility load cannot be interrupted. Results have shown that aggregations of small responsive loads can provide greater reliability than fewer numbers of large generators [27]. Result of study in Figure 10 shows that large numbers of individually less reliable responsive loads can provide greater aggregate reliability than fewer large generators [27]. In the research, contingency reserves were being supplied by six generators capable of providing 100MW of response with 95% reliability. Study found that 74% of all six generators could respond to contingency events and the probability that at least five will respond is 97%. In contrast, contingency reserve being supplied from aggregation of 1200 responsive loads of 500 kW with 90% reliability delivered typically 540 MW but never delivered less than 520. The results illustrate that aggregate load response is much more predictable [27].

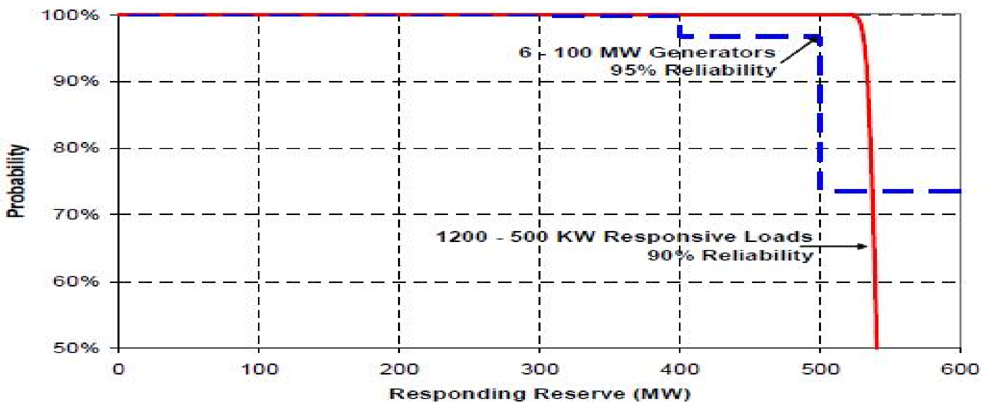


Figure 10 : Larger numbers of individually less reliable responsive loads can provide greater reliability than fewer large generators [27].

If individual generators used in contingency reserve fails to respond, it leads to serious consequences in power system. Thus system operator has to observe the real time response of the generator supplying contingency reserves. In contrast individual loads are small and the failure of an individual load respond is insignificant to bulk system reliability. Similarly, responsive loads can support a monitoring system to inform the system operator of the resource availability. Moreover, forecasting for accurate assessment of available spinning reserve from responsible load is also possible. Such forecast could be based on expected temperature and humidity, day type and time of day [27].

When the supply becomes greater than the demand to mitigate over frequency different energy storage schemes are used. Excess energy in the electrical form cannot be stored in the same form; hence it is stored in the form of electromagnetic, electrochemical, kinetic or potential energy [29]. Each scheme requires energy conversion from one form to another.

Figure 17 shows the different energy storage schemes used in the electric power system. Batteries, Flywheel, Super conducting Magnetic Energy Storage (SMES), and capacitors are used depending on amount of power required to be stored [30].

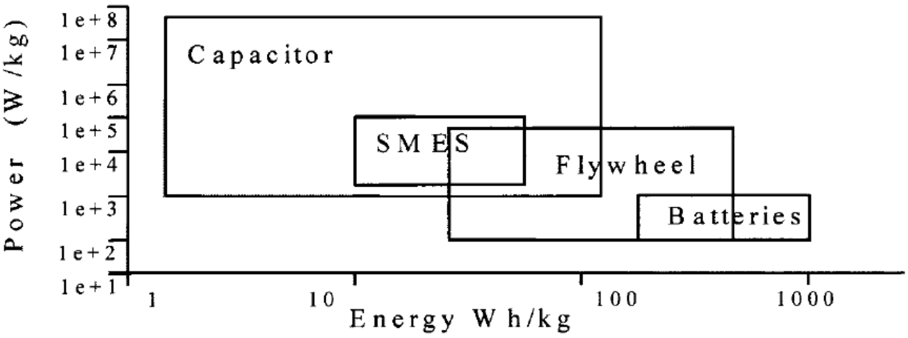


Figure 11: Specific power Vs. Energy Storage scheme used [30].

3.5 Energy Storage Schemes

3.5.1 Energy Efficient Super Capacitor Energy Storage System

These are made up of carbon and have large effective surface. These systems can have a capacitance value up to the range of thousands of farad. Moreover, absence of electrochemical reaction for energy conversion and presence of electric charge absorption and desorption phenomenon during charging and discharging they charges or discharges gives these system long life [31].

3.5.2 Super conducting Magnetic Energy Storage (SMES)

SMES system stores energy in the magnetic field generated by the DC current flowing through a super conducting coil. Super conducting coils are kept at cryogenic temperature maintained by a cryostat or dewar containing helium or nitrogen vessels. SMES units are connected to an AC power system by a conversion/conditioning system [30].

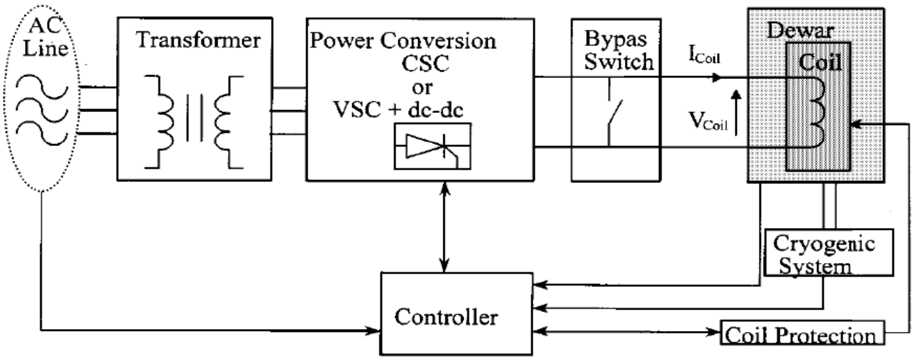


Figure 12 : Typical SMES System [30].

3.5.3 Battery Energy Storage System

Batteries store electric energy through electrochemical reaction. It consists of low voltage/power battery modules connected in parallel and series to match required capacity. Most important features battery system incorporate are high energy density, and capability, cycling capability, life span. A power conversion interface is required to connect to AC system because charge is stored as DC in battery system. Battery Energy system is frequently used in several power system applications such as area regulation, area protection, spinning reserve, and power factor correction [29].

3.5.4 Flywheel Energy Storage System

Flywheel energy system consists of Flywheel (FW), Electrical Machine (EM), Power Electronic system (PE) and Supply Lines (L) all equipped are with bidirectional power flow feature as shown in Figure 13. J_{FW}, ω_{FW} and P_{FW} are the resultant inertia, angular speed, and power stored in the flywheel respectively. Decrease in ω_{FW} results in energy being taken out from flywheel. Similarly, increase in ω_{FW} results is energy being fed to the flywheel. Hence, during excess of power in the system when $P_{FW} < 0$, machine is operating as motor. Similarly, when $P_{FW} > 0$, electrical machine is operating as generator [31].

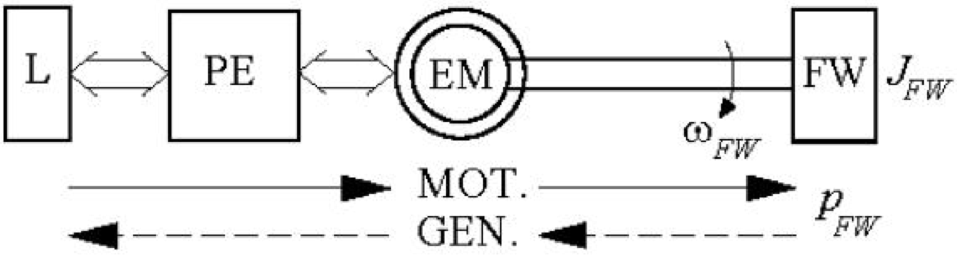


Figure 13: Flywheel Energy Storage System [31].

Reliability, long life, and fast response as compared to other energy storage have resulted in extensive use of Flywheel energy system [31]. Figure 14 shows the working of flywheel in power system. P_G and P_{FW} are the wind turbine power and flywheel power respectively. So when ever PG fluctuates from its average value

P_{Gav}, flywheel will come into operation. When $P_G > P_{Gav}$, power is fed to the flywheel, thus charging it and vice versa.

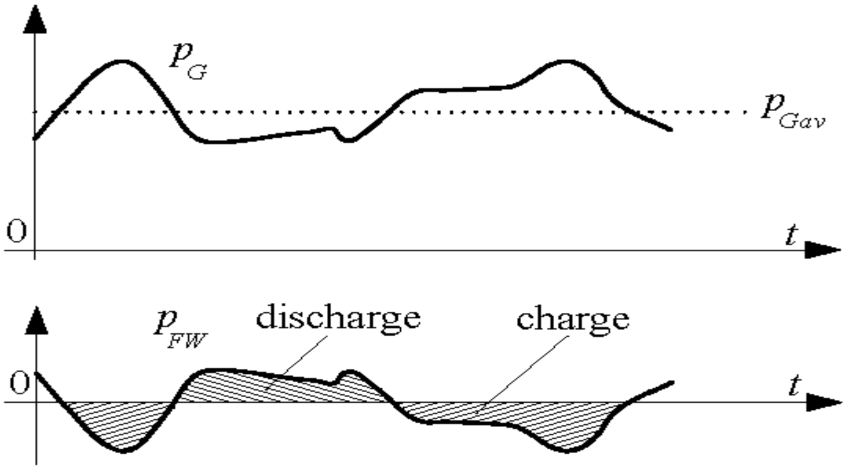


Figure 14: Charging and discharging of flywheel according to fluctuation in wind power [31].

Section 3.5 explains the commonly used energy storage system for power system stability and regulation. Technically, they seem to provide better solution to the stability of the system. However, utility companies suffer financially each time these energy storage systems are activated as generated excess power has to be dumped so that the power system maintains its stability. Section 2.9 and 2.10 explains that frequency responsive loads can provide better economic solution to the utility company. Whenever over frequency occurs in the power system, frequency responsive loads can be activated and energy can be transferred to these loads.

CHAPTER 4

4. Discussion and Results

A novel approach of utilizing heating energy via electric space heater to compensate heat loss from a house as frequency reserve has been tried to explore in this section. Electric space heater stores heating energy required for a house during off peak period. Amount of heating energy stored in the electric space heater during off peak period is approximately equal to the heat loss occurring from the house round the clock. Thus stored energy is then discharged during the rest of the day to maintain the required indoor temperature.

As explained in section 2.5, the penetration of renewable energy such as wind power, and solar photovoltaic is increasing in the existing power system. Uncertainty and variability are always associated with renewable energy. Any unpredicted excess power produced from the renewables resources at any time have to be disposed or consumed immediately. If not disposed, stability of power system will be affected as it leads to the over frequency problem in the grid.

Electric space heater exhibit properties required for a frequency responsive load as explained in Section 3.4. Hence, fixed time operation of electric space heater to store heating energy can be modified to instantaneous operation whenever excess energy from the renewables is generated to control the over frequency. For that, heat loss from a house must be known any instant. Heat loss from a house is dependent on external temperature. So, with known heat loss profile the required heating energy to compensate heat loss can be estimated. Thus, during excess generation from the renewables above estimated heating energy can serve as frequency reserves.

4.1 Calculation of Heat loss from a House

Heat is a form of energy which transfers among particles in a substance by means of kinetic energy of that particle. It is a state quantity and is expressed in terms of joules [32]. Similarly, transfer of heat due to temperature difference is often known as heat flow and is expressed in terms of watt (W).

Heat transfer occurs between two systems due to of temperature difference between them. Heat flows from the warmer system to the cooler system until a thermal equilibrium is reached between these systems. Heat transfer occurs via conduction, convection, and radiation.

Heat loss through a house depends upon difference in inside and external temperature of house, insulation and area of building materials. Heat loss from house mainly occurs via fabric heat loss (Q_f) and heat loss through ventilation (Q_v) [33].

Mathematically, fabric heat loss can be expressed as

$$Q_{f} = A \times (Temprature_{inside} - Temprature_{outside}) \times U \text{ ………………… } (4.1)$$

$$Q_{f} = A \times \Delta T \times U \text{ ……………………………………………………….. } (4.2)$$

where,

Q_f = Fabric heat loss [W]

A= Area of the house element from which heat is being transferred [m^2]

ΔT= Difference in internal and external temperature [℃ or K]

U= Coefficient of thermal conductivity [$W/m^2 K$]

U values also often known as heat transfer coefficient represent the conductivity of different elements of house. It is defined as the rate of heat flow in watts (W) through an area of 1 square meter (m) for a temperature difference across the structure of 1 ℃ degree centigrade or Kelvin (K). It is also inverse of thermal resistance (R) and has SI units of $W/m^2 K$. These values are country specific and the U value used for different elements of house in this thesis is as recommended by Ministry of Environment, Finland as shown in Table 1 [34].

Elements of the House	**U values (W/m^2°C)**
External wall	0.25
Floor	0.16
Roof	0.25
Windows	1.8
Doors	0.9

Table 1: U values required for different elements of house in Finland.

A typical Scandinavian house is considered in this thesis for calculation of heat loss [35]. The layout and dimension of the house is presented in Appendix A.

The indoor temperature is maintained according to customer thermal comfort label. ASHRAE 55-2004 and ISO 7730 have defined thermal comfort as ‘specific combination of thermal conditions that will elicit the desired physiological state of comfort’. World Health Organization (WHO) recommends temperature of the main living area to be 21° C and for the rest of the home to be 18° C [36].

The indoor temperature has been set as given in Table 2 for the week days and weekends.

Setting	Time	Temperature to be maintained weekdays	Temperature to be maintained weekend
Wake	6:00 to 8:00	21° C	21° C
Day	8:00 to 18:00	16° C	21° C
Evening	18:00 to 22:00	21° C	21° C
Sleep	22:00 to 6:00	16° C	16° C

Table 2: Setting of Indoor Temperature for weekdays and weekends [36].

The external temperature used in this thesis is taken from Kainuu Region of Finland is as shown in Figure 15.

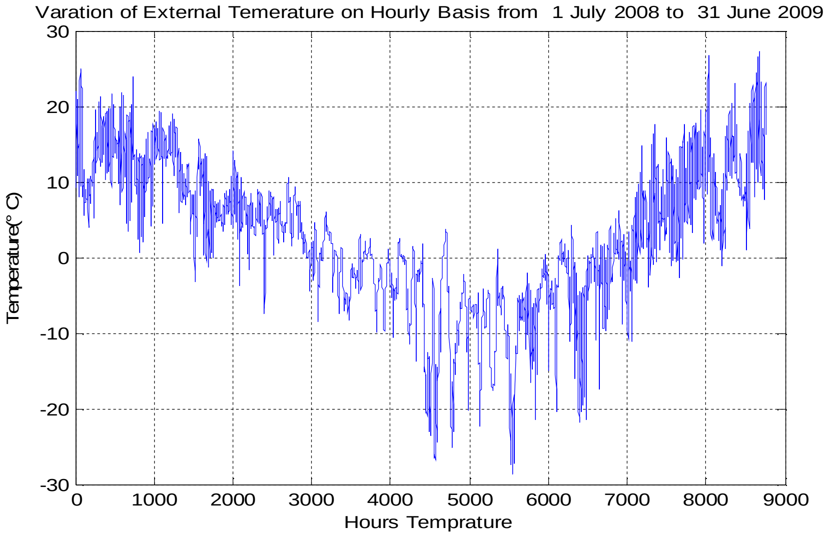


Figure 15: External Temperature from 1st July 2008 to 31st June 2009.

The maximum temperature in summer is 27.2 °C and minimum temperature in winter was -28.7 °C.

Given the dimensions of the building elements, U values and the indoor temperature, for a given external temperature, fabric heat loss can be calculated using Equation 4.1.

Similarly, heat losses through ventilation (Qv) can be calculated as [33]:

$$Q_v = N \times V \times Sp_{\cdot ht} \times \Delta T \quad \ldots\ldots\ldots \quad (4.3)$$

where,

Q_v= heat losses through ventilation [W]

N = Air change Rate

V = Volume of Room being considered [m^3]

$Sp_{\cdot ht}$= specific heat factor of the air [kJ/kg K]

The value of air change rate and specific factor of the air used in the calculation are appended in Appendix B.

Heat loss through each element of building can be calculated using Equation 4.1 and 4.2. Furthermore, calculated heat loss from all the elements of the house is then summed up to get total heat loss from the house on hourly basis.

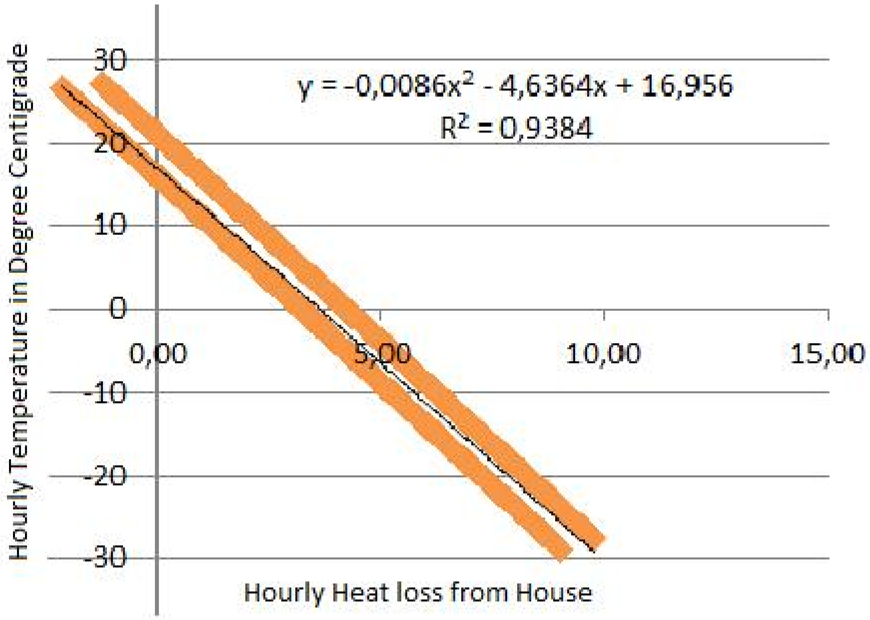
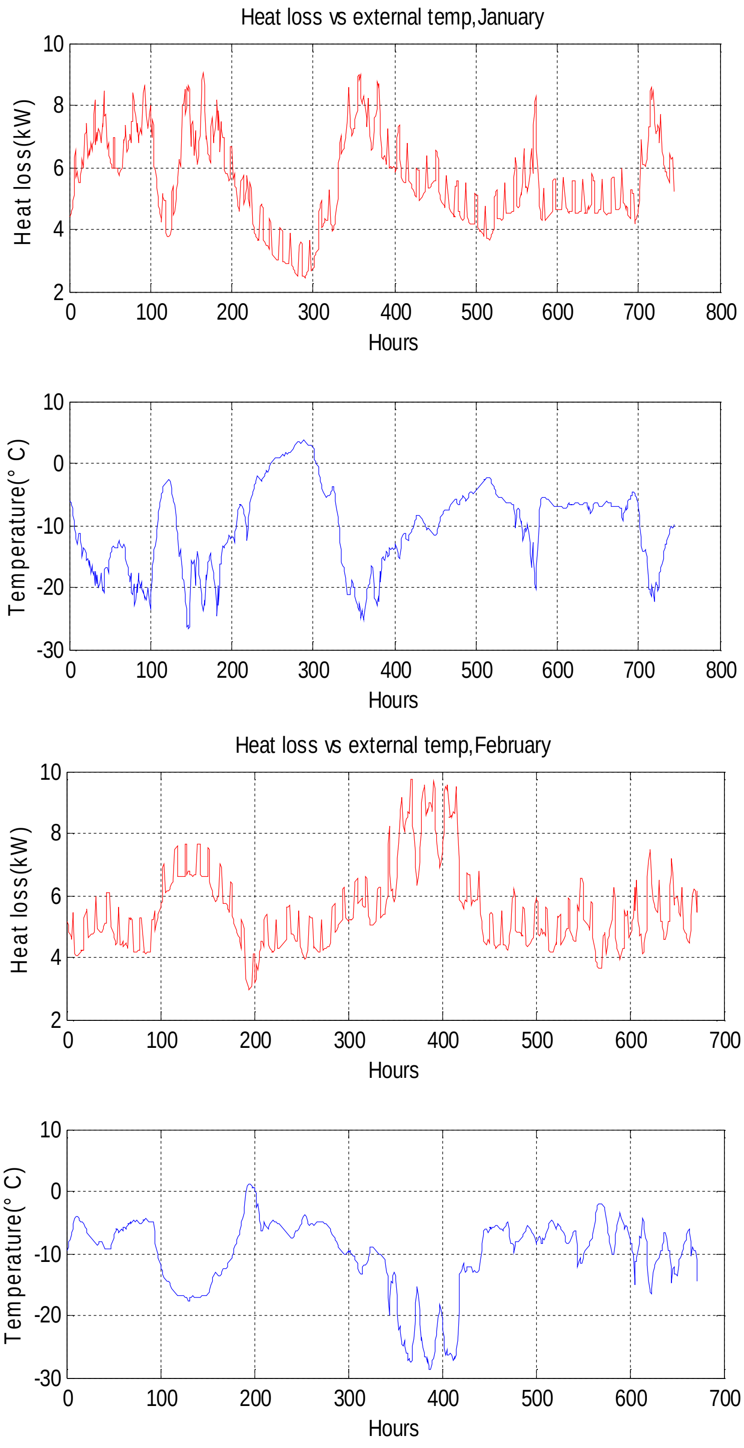


Figure 16: Correlation between external temperature and heat loss from the house.

Figure 16 shows that heat loss from a house is correlated with temperature. The correlation coefficient between external temperature and heat loss from the house is -0.9681. It explains that when external temperature is minimum, heat loss will be high and vice versa. During winter the external temperature is low and the heat loss from the house will be high. Heating energy equivalent to losses from house required to maintain the indoor temperature at desired level. Similarly, during summer the indoor temperature becomes lower than the external temperature and thus creating a reverse heat flow from outside to inside. Hence, heating energy would not be required. The heat loss from house according to external temperature for different month on hourly basis are shown in Figure 17, 18 , 19 , 20, 21, 22 for the year 2010.



Heat loss vs external temp,January

Heat loss vs external temp,February

Figure 17: Heat Loss and External Temperature for January and February, 2009

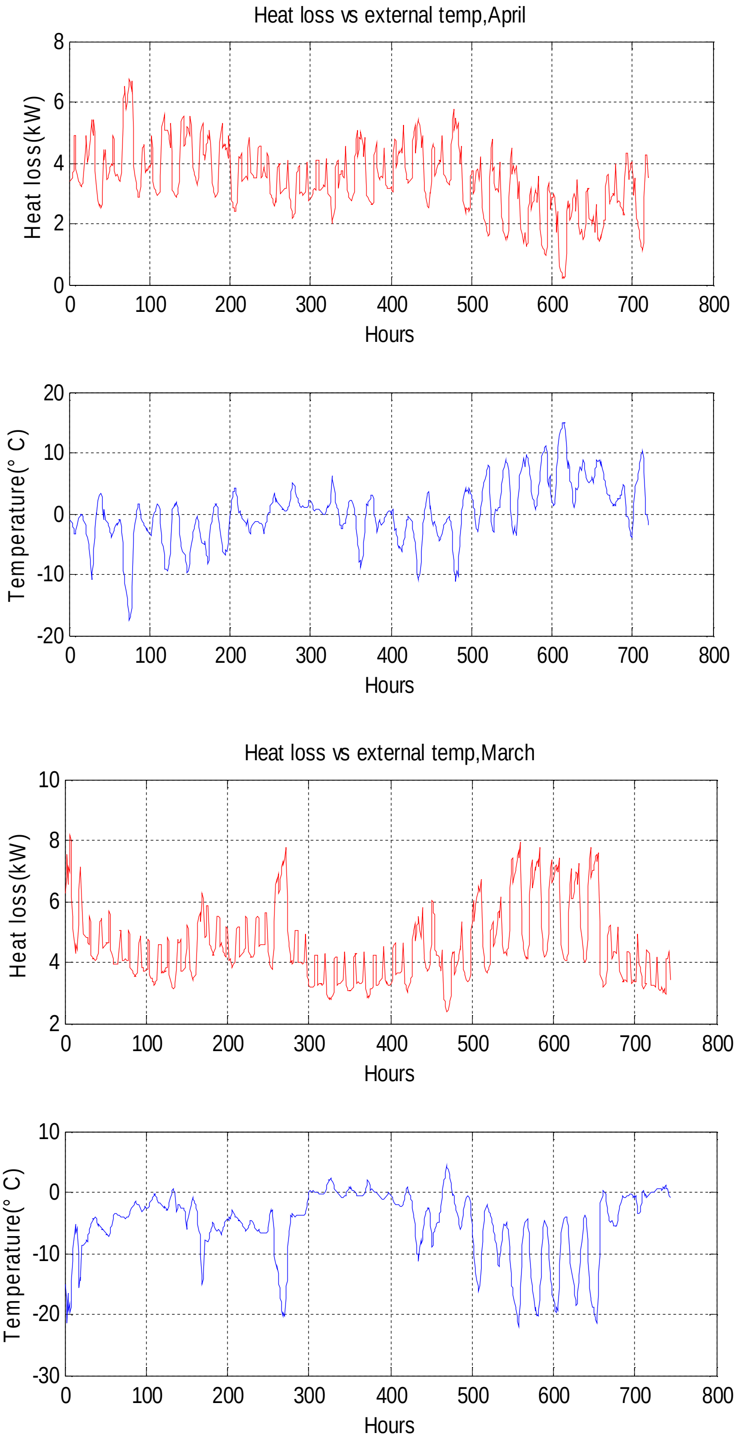


Figure 18: Heat Loss and External Temperature for March and April, 2009

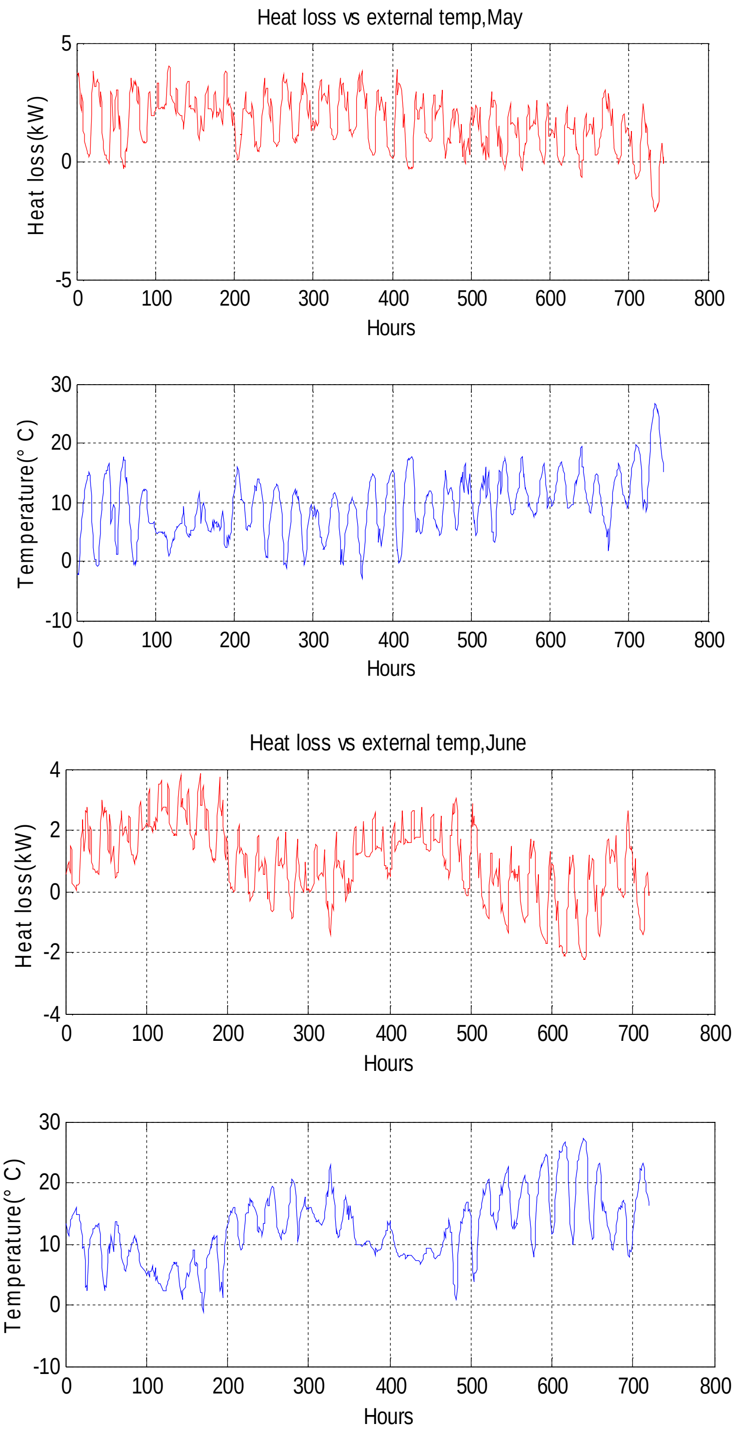


Figure 19: Heat Loss and External Temperature for May and June, 2009

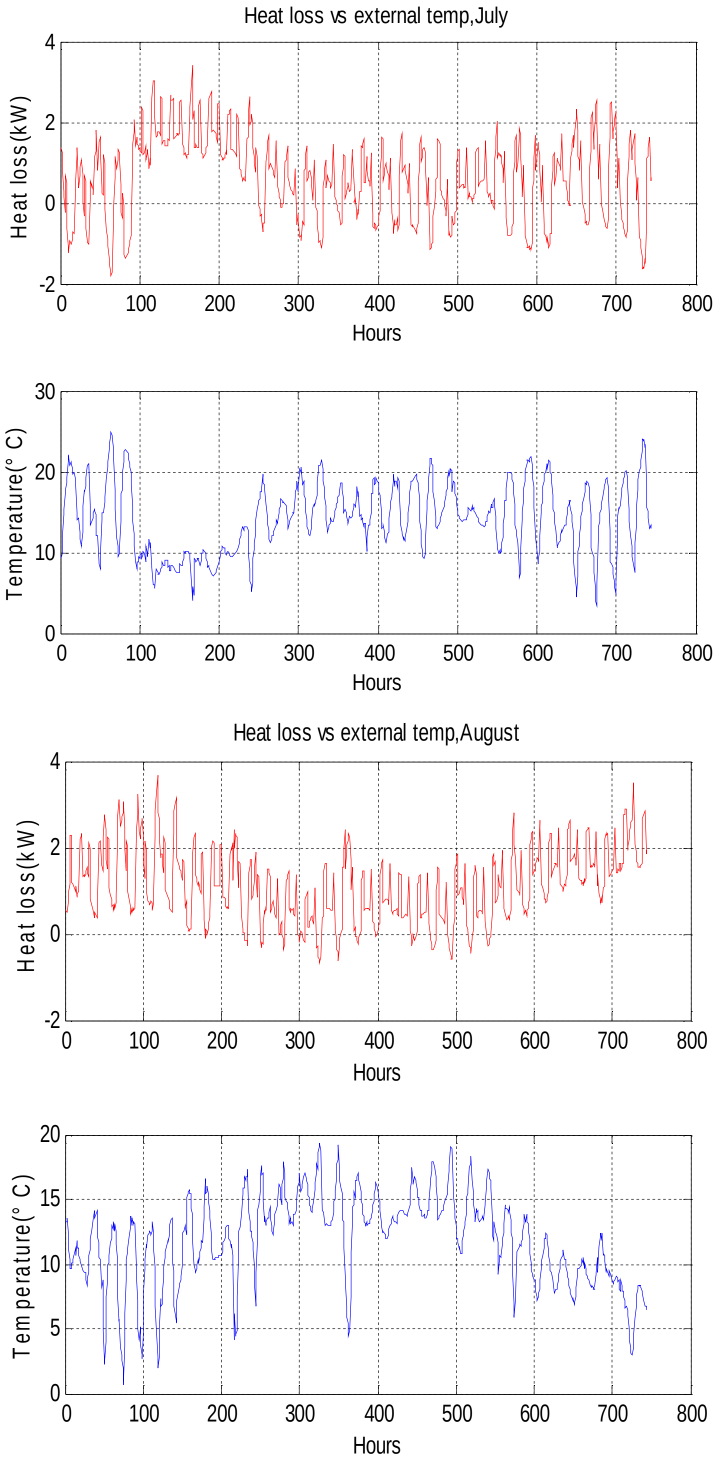


Figure 20: Heat Loss and External Temperature for July and August, 2009

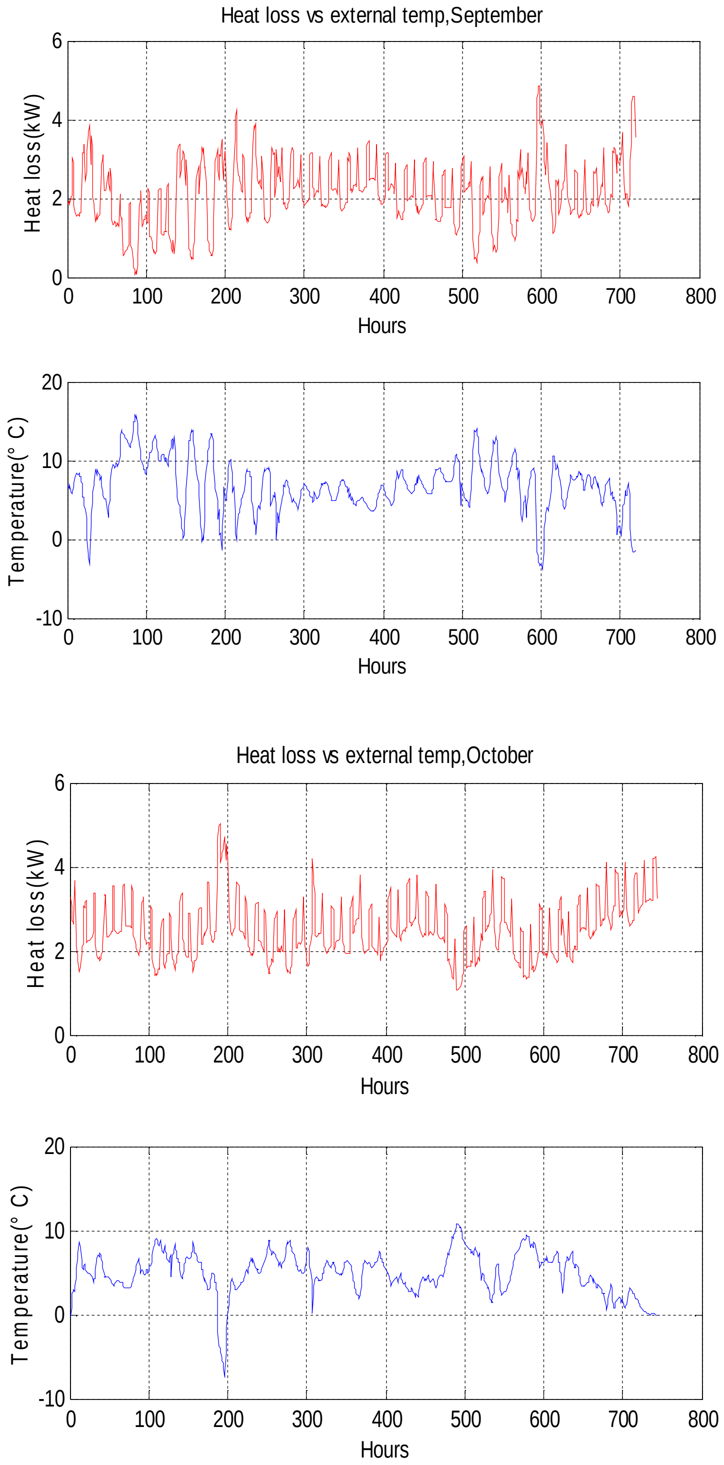


Figure 21: Heat Loss and External Temperature for September and October, 2009

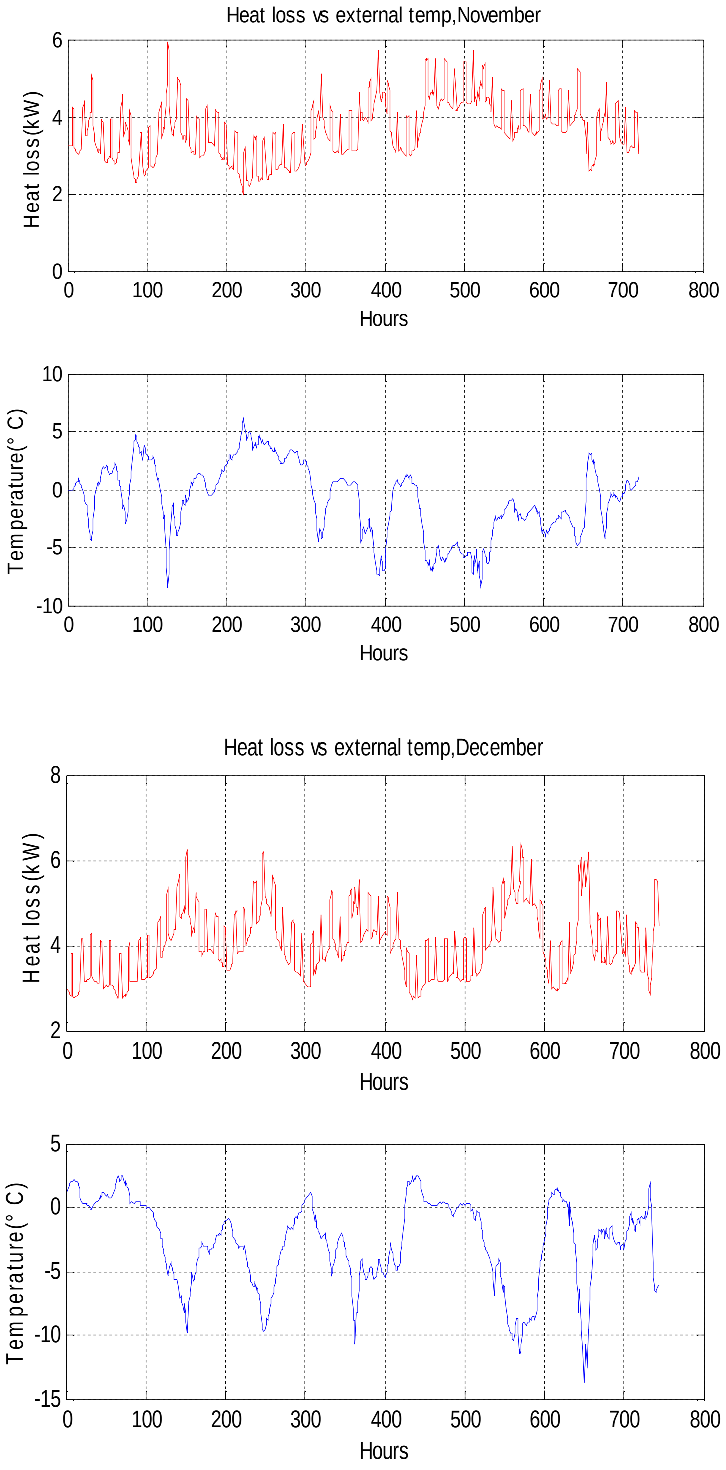


Figure 22: Heat Loss and External Temperature for November and December, 2009

As seen from Figures 17, 18, 19, 20, 21, 22 heat losses from a house vary according to the external temperature. It is high during the winter period from November to March and decreases during summer when external temperature sometimes will be even higher than indoor temperature. Figure 23 shows the average temperature and hourly heat loss from home on hourly basis throughout the year.

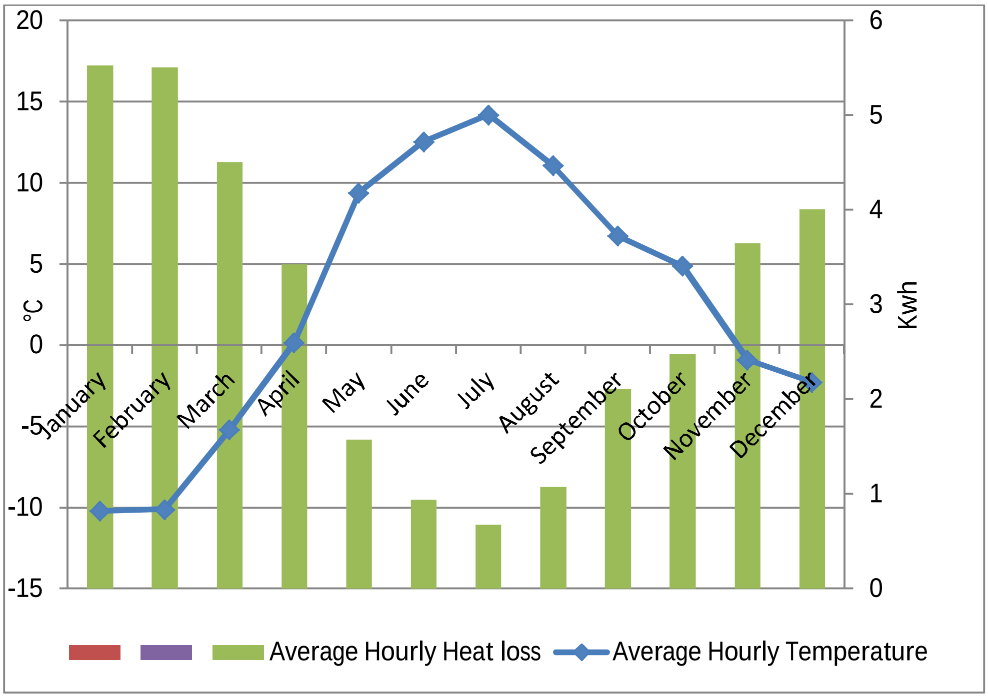


Figure 23: Hourly Average Temperature and Heat loss on monthly basis.

4.2 Power System Frequency Dynamics

Generator inertia is stored in rotating masses (rotor, turbines(s) and shaft) in the form of kinetic energy. When there is sudden increase in generated output power it results to increase in speed of the machine or frequency. Mathematically, Kinetic energy stored in rotating mass can be expressed as [5].

$$W_k = \frac{1}{2} J \omega^2 \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(4.4)}$$

Where

W_k = Energy Stored in the rotating masses [Ws].

For the Nordic system, W_k = 300,000 MWs.

J= Inertia of the machine [kg.m^2].

ω = Rotational velocity of the machine [rad/s].

The inertia constant (H) is the stored energy at synchronous speed per volt-ampere rating of machines and provides an indication of the duration that generator can provide nominal power with the help of kinetic energy stored in rotating machines [46]. Mathematically it can be expressed as follows [5].

$$H = \frac{W_k}{S} = \frac{J\omega^2}{2\,s} \quad \ldots\ldots \quad (4.5)$$

where S is the nominal apparent power of generator (VA).

Similarly, the relation between change in load balance and energy stored is given by

$$\Delta P = \frac{\delta W_k}{\delta t} \quad \ldots\ldots \quad (4.6)$$

Where ΔP = $P_{generated}$- $P_{load.}$

Solving for W_k from Equation 4.4, we get

$$\Delta P = \omega J \frac{d\omega}{dt} \quad \ldots\ldots \quad (4.7)$$

Rearranging Equation 4.4, we get

$$\omega J = \frac{2W_k}{\omega} \quad \ldots\ldots \quad (4.8)$$

Substituting Equation 4.8 in Equation 4.7, we get

$$\frac{d\omega}{dt} = \frac{\Delta P \times \omega}{2W_k} \quad \ldots\ldots \quad (4.9)$$

With $\omega = 2\pi f$, Equation 4.9 can be rearranged as

$$\frac{df}{dt} = \frac{\Delta P \times f}{2W_k} \quad \ldots\ldots \quad (4.10)$$

Equation 4.10 can be generalized as

$$\frac{df(t)}{dt} = \frac{\Delta P(t) \times f(t)}{2W_k} \quad \text{.. (4.11)}$$

Thus, the rate of change of frequency at any instant mainly depends upon the change in load balance and the frequency at that instant.

Frequency is an indicator of the balance between electricity generation and consumption [37]. Frequency stability is a high priority for a stable operation of power system because synchronization and stability of power system is dependent on the system frequency. Thus, system frequency has to be maintained within the specified range. Normal operation of the continental European grid is between 49.95 and 50.05 Hz [38]. Normal range of frequency in Nordic power system is from 49.90 to 50.10 Hz [14]. Frequency should not fluctuate out of the range for more than 1200 minutes per year [38]. The standard EN50160, allows a frequency deviation up to +/- 0.5 Hz if there is a sudden change in generation or load.

Equation 4.10 shows that the system frequency remains constant if net change in load balance is zero. i.e. $\Delta P=0$. A positive or negative change in load balance results either increase or decrease in the system frequency from its nominal value respectively.

Figure 26 shows the flowchart for calculating the frequency of Nordic power system using Equation 4.11. Initially, the Nordic system frequency is assumed to be balanced at 50 Hz. When change in net load is zero, frequency remains constant at 50 Hz. But during excess generation (E_{gen}), change in net load (ΔP) is positive, thus it increases the system frequency. The Matlab code for frequency calculation is presented in Appendix C. System frequency is calculated for excess power that is going to be injected on hourly basis.

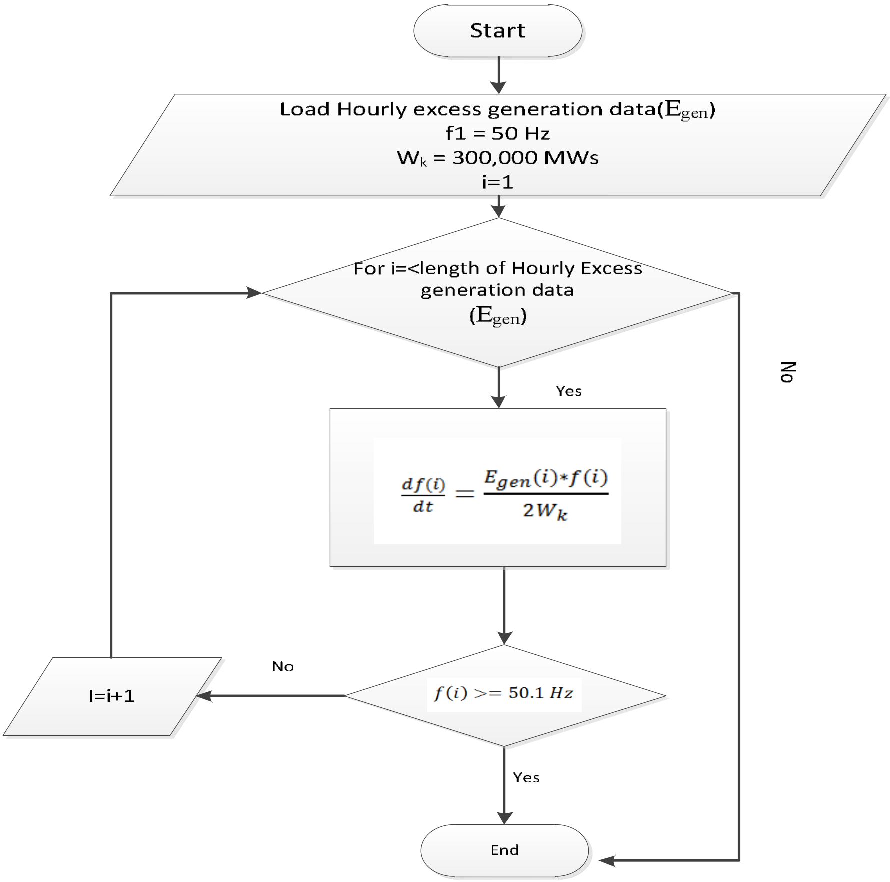
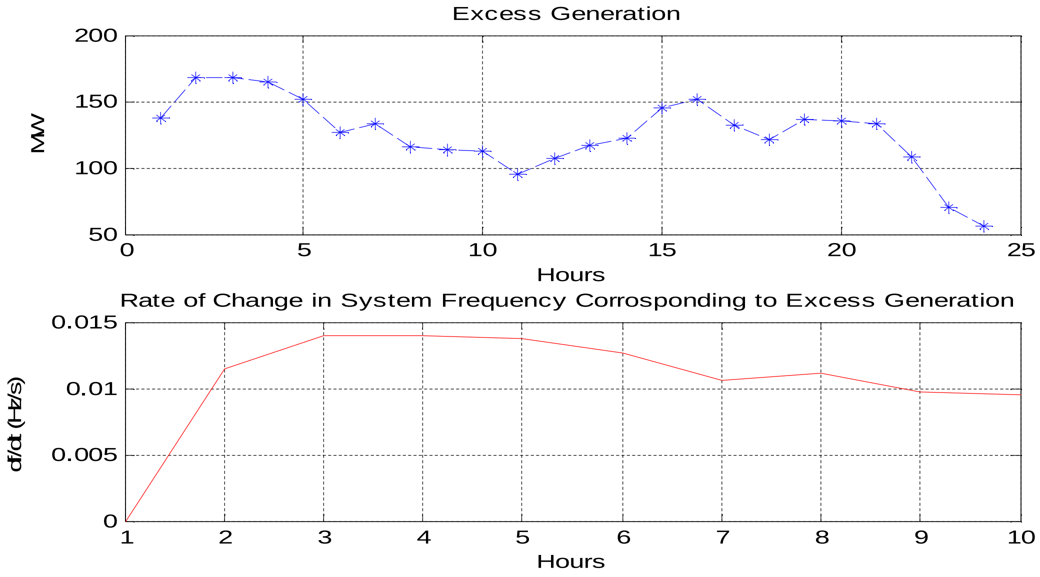


Figure 24: Flow chart for System frequency calculation


Excess Generation

Rate of Change in System Frequency Corrosponding to Excess Generation

Figure 25: Frequency deviation of Nordic Transmission System with injection of excess power from renewables.

With a continuous injection of excess energy (E_{gen}) generated as shown in Figure 25, the frequency of the Nordic transmission will deviate from the limit unless the generating unit are tripped off or energy storage schemes are activated as explained in section 3.5.

4.3 Frequency Reserves Treating Hourly Loss as Required Heating Energy.

Heat loss profile for a house calculated in Section 4.1 has been treated as the minimum heating energy required at that instant. So, excess generated energy can dumped to mitigate over frequency problem. The excess generated energy (E_{gen}) equivalent to required heating energy (H_{req}) at that instant can be transferred.

The output power data used in simulation in this thesis is taken from the power produced by the wind power from Eastern Denmark. It is assumed as excess generation that is going to be injected into the Nordic transmission system so that the output power variation becomes realistic throughout the year. Secondly, it is assumed that there are 50,000 houses to get considerable amount of frequency responsive loads calculated in Section 4.1 via electric space heater.

Excess generation (E_{gen}) occurring on hourly basis is matched with required heating energy (H_{req}). If heating energy (H_{req}) is more than excess generation (E_{gen}), excess generated energy (E_{gen}) equivalent to heating energy (H_{req}) is transferred to electric space. Thus, change in load balance (ΔP) equals to zero at that instant and frequency remains constant. Remaining required heating energy is stored or charged during the off peak period.

Similarly, if excess generation (E_{gen}) is more than the amount of required heating energy (H_{req}), excess generation equivalent required heating energy (H_{req}) at that hour is transferred to the electric space heater. However, the leftover excess generation is injected to the system and will cause an equivalent positive net load change and the system frequency increases. In the next hour, if excess generation (E_{gen}) still exceeds required heating energy (H_{req}), equivalent leftover excess generation is again injected to the system. The system frequency will increase again and attain the value based on positive change in load balance caused by the amount of cumulative excess generation that was injected into the system. If the system frequency is going to increase more than 50.1 Hz, the generating units must be cut off from the system. Thus, in such scenario frequency of power system cannot be controlled to remain within operational limits.

However, if we can reduce or if possible nullify the amount cumulative of leftover excess energy injected in the system to lower the positive load balance (ΔP) frequency can be decreased to retain its nominal value (50 Hz). For that operation, the availability of remaining heating energy is checked in the next hour. If there is still demand of heating energy after consuming the excess generation, energy equivalent to remaining heating energy is transferred from the system to the space heater. This procedure is continued till the frequency reaches 50 Hz.

The flowchart for matching excess generation with available heating energy on hourly basis is shown in Figure 28. Difference between required heating energy and possible excess generation is calculated. Then, possible values of change in load balance (ΔP) on hourly basis hourly basis is manipulated as explain above and stored in Frequency Varying Load. In Cumsum array current value of leftover excess generation is stored and in Prevcumsum array cumulative values of leftover excess generation is stored. The Matlab code for balancing excess generation (E_{gen}) with required heating is (Hr_{eq}) is presented in Appendix C.

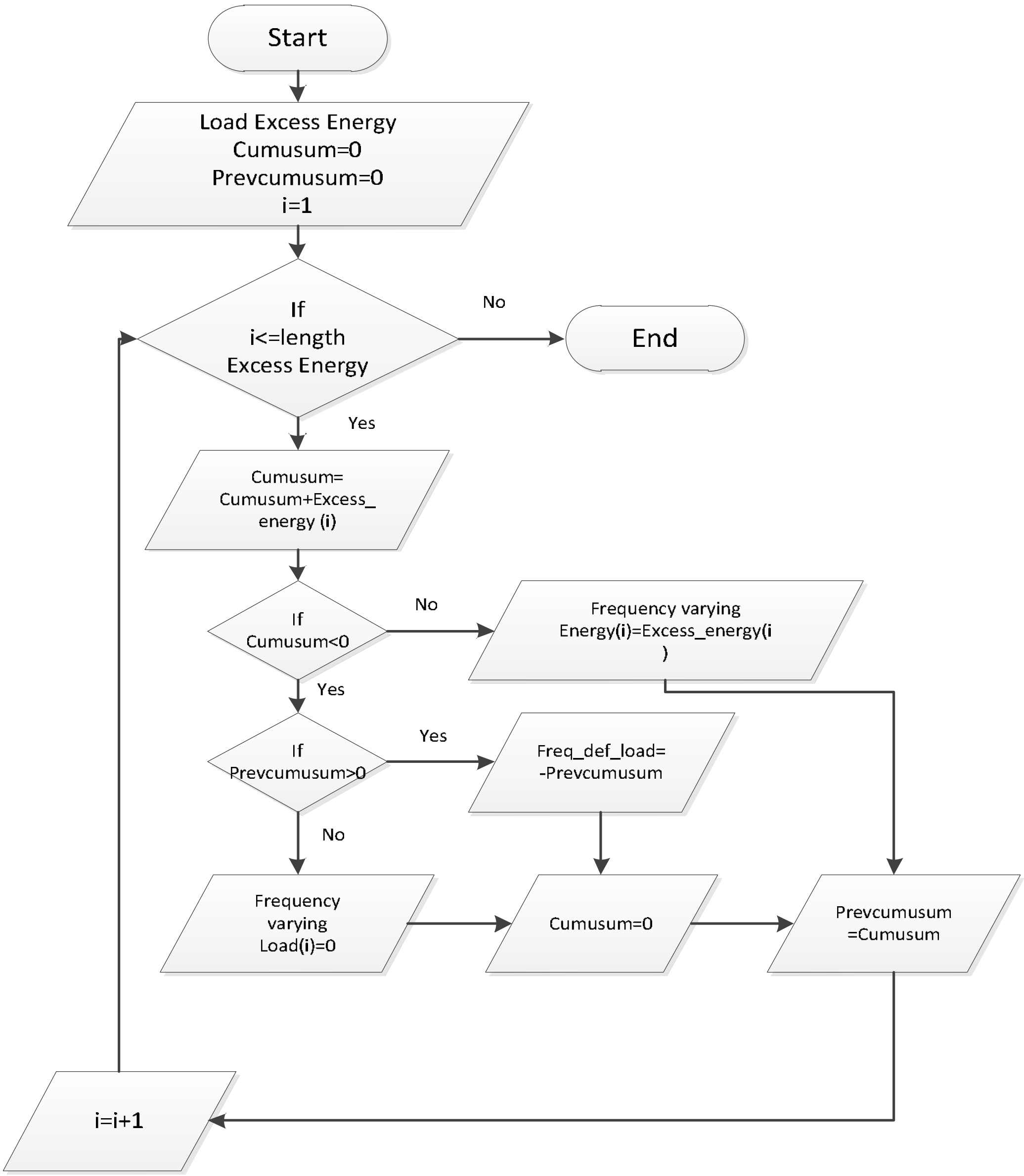


Figure 26: Flowchart for ΔP calculation utilizing heating energy.

Now, with thus obtained value of change in load balance on hourly basis the system frequency is calculated. Flowchart presented on Figure 27 shows the calculation of Nordic Transmission System after utilizing the heating energy available as frequency controlled reserves. .

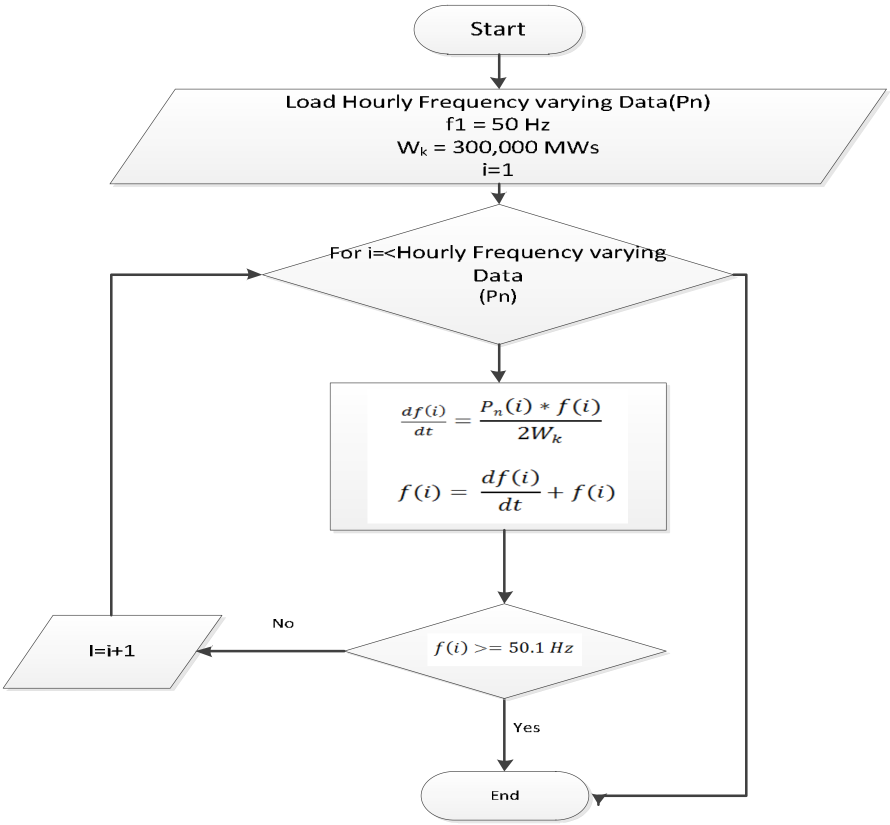


Figure 27: Flowchart for Controlling Frequency of Nordic Transmission System.

The required heating energy for round the clock is usually stored during the night time when the electricity price is cheap. The off peak period of eight hours has been considered for this and it spans from 12 midnight to 8 am in the morning. The price used in calculation has been downloaded from Nord pool Spot for the year 2010.

Similarly, price of using energy as a frequency reserve is also calculated. The cost of energy used for heating instantaneously to compensate excess generation is calculated using the price of electricity set for that time. Any leftover heating energy after utilizing in frequency control is stored during the off peak period.

The hourly price of electricity set for balanced condition is used in calculating the energy cost for using frequency reserves. The cost of using energy for heating load during frequency control has always came greater than the off peak period.

4.4 Simulation Result.

With the available required heating energy profile and assumed probable excess generation, each day was simulated on hourly basis throughout the year. During summer the heating energy requirement is almost zero, thus it is obvious frequency control is not possible.

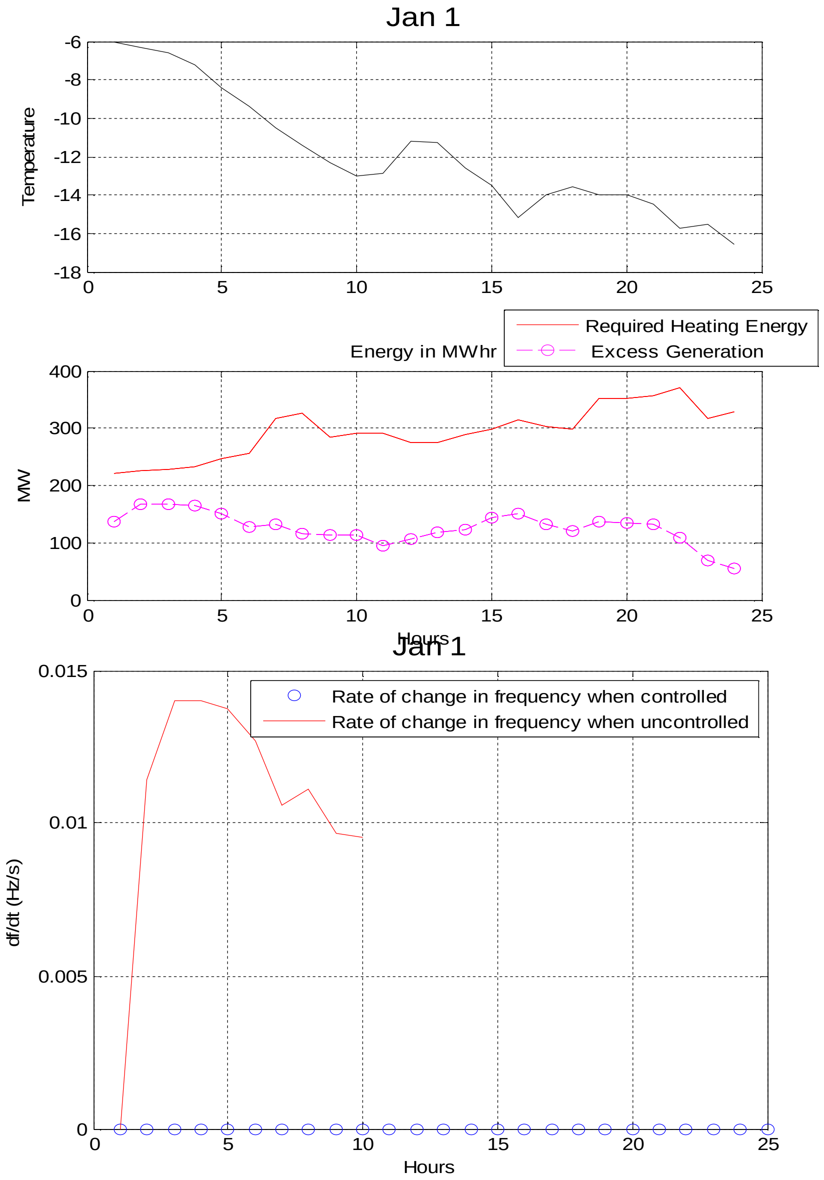


Figure 28: Frequency Control Using heating energy for Jan 1.

As seen from Figure 28, the required heating energy (H_{req}) is more than the excess generation (E_{gen}). The excess generation (E_{gen}) can has been transferred to the heating load thus ensuring the stability of the network.

The cost of storing heating energy in off peak period is € 0.0074077 per kWh per customer. During frequency control customer has to pay € 0.017782 per kWh. The difference between using energy during frequency control and off peak hour is € 0.010374 kWh. This is due to the fact that electricity price at balanced condition is used.

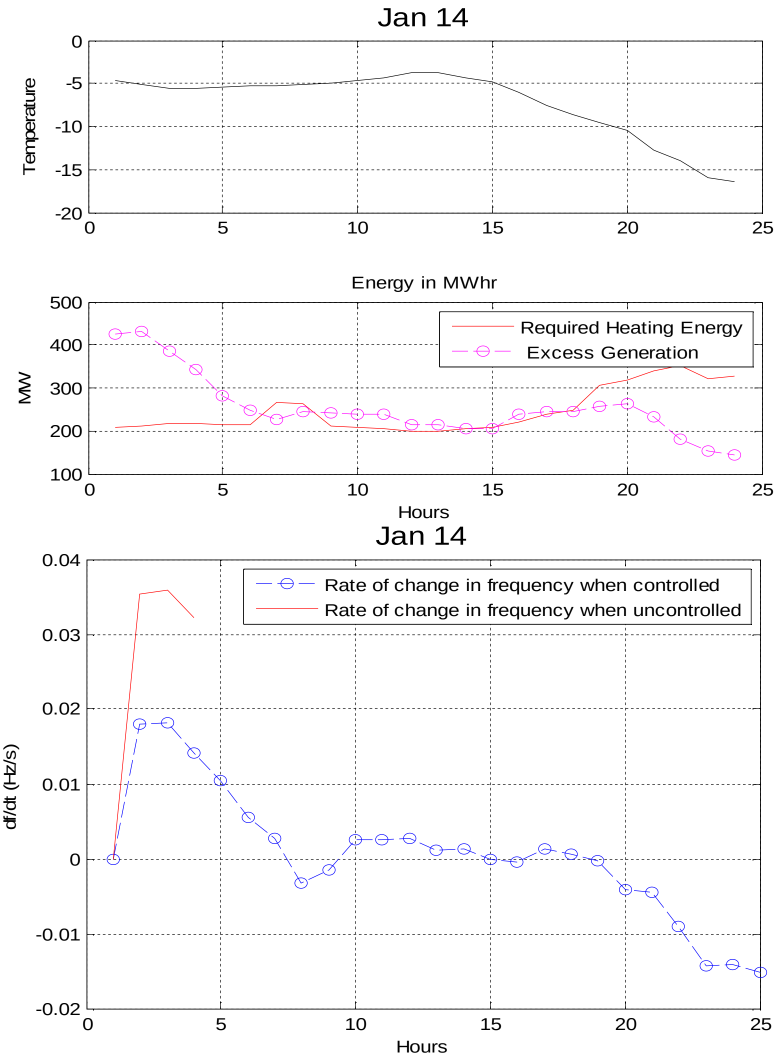


Figure 29: Frequency Control Using Heating Energy for Jan 14.

Figure 29 show that for initial 6 hours the excess generation (E_{gen}) is around 215 to 50 MW more than required heating energy (H_{req}). So, after matching excess generation (E_{gen}) with required heating energy (H_{req}), leftover excess generation of 215 to 50 MW is injected into the system. Thus it will increase the system frequency from its nominal value of 50 Hz to 50.06 Hz. However, after 6th hour required heating energy (H_{req}) becomes greater than excess generation (E_{gen}) for few more hours. Thus frequency will now remain constant 50.06 Hz. As, kinetic energy stored (W_k) of the Nordic system is very high, frequency will decrease to 50 Hz at very slow rate. So to decrease frequency quickely, availability of remaining required heating energy can be utilized. Equivalent amount of energy can be released from the system to fulfill remaining required heating energy. Hence, it will aid in the decrease in frequency to its nominal value of 50 Hz. The cost of storing heating energy in off peak period is € 0.0061985 per kWh per customer. During frequency control customer has to pay € 0.011709per kWh. The difference between using energy during frequency control and off peak hour is € 0.0055103 kWh.

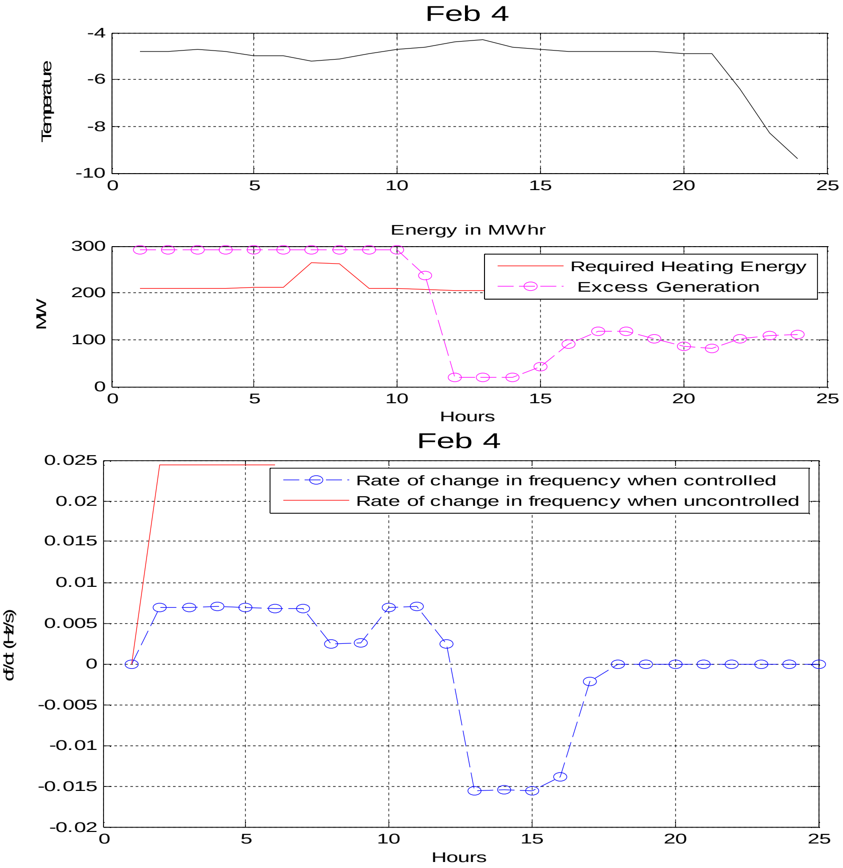


Figure 30: Frequency Control Using Heating Energy for Feb 4.

In this case, initially the frequency rises as available required heating energy (H_{req}) is less than the excess generation (E_{gen}). Once, required heating energy (H_{req}) becomes greater than excess generation (E_{gen}), the leftover remaining heating energy can be used to decrease the frequency as explained for Figure 29. The cost of storing heating energy in off peak period is € 0.005895 per kWh per customer. During frequency control customer has to pay € 0.011575 per kWh. The difference between using energy during frequency control and off peak hour is € 0.0056798.

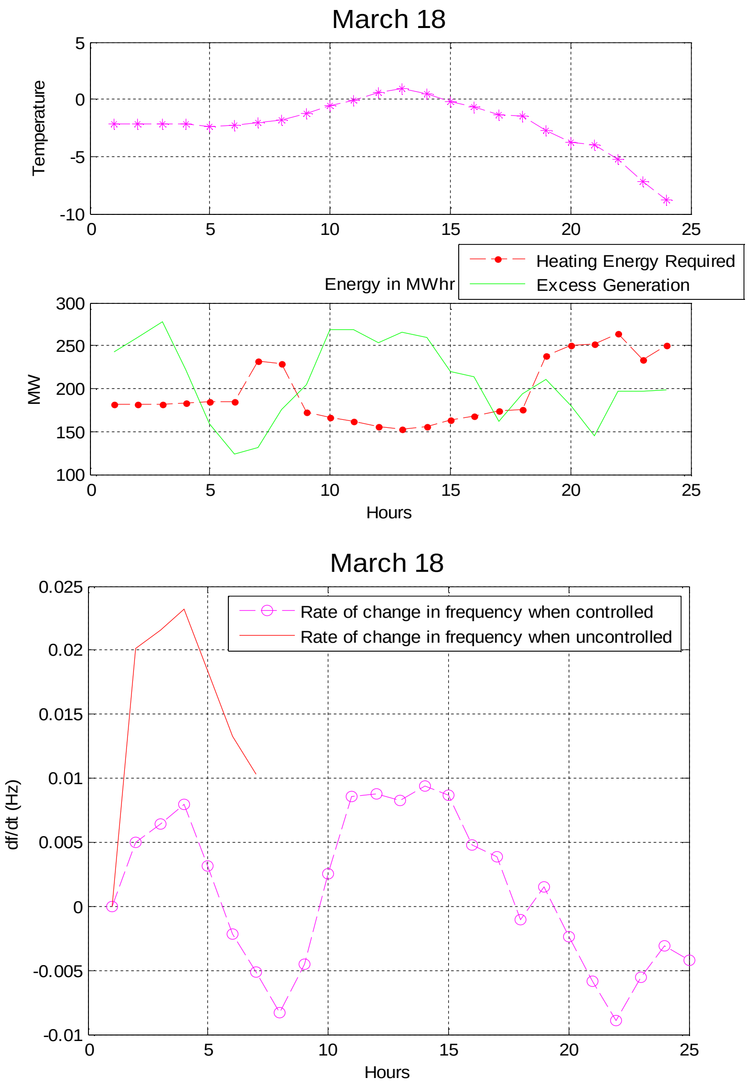


Figure 31: Frequency Control Using Heating Energy for March 18.

In this case, similar to Figure 30 when the excess generation (E_{gen}) is greater than the heating energy (H_{req}), system frequency increases and is reduced as the leftover remaining heating becomes available. The cost of storing heating energy in off peak period is € 0.005275 per kWh per customer. During frequency control customer has to pay € 0.0085364 per kWh. The difference between using energy during frequency control and off peak hour is € 0.0032615 kWh.

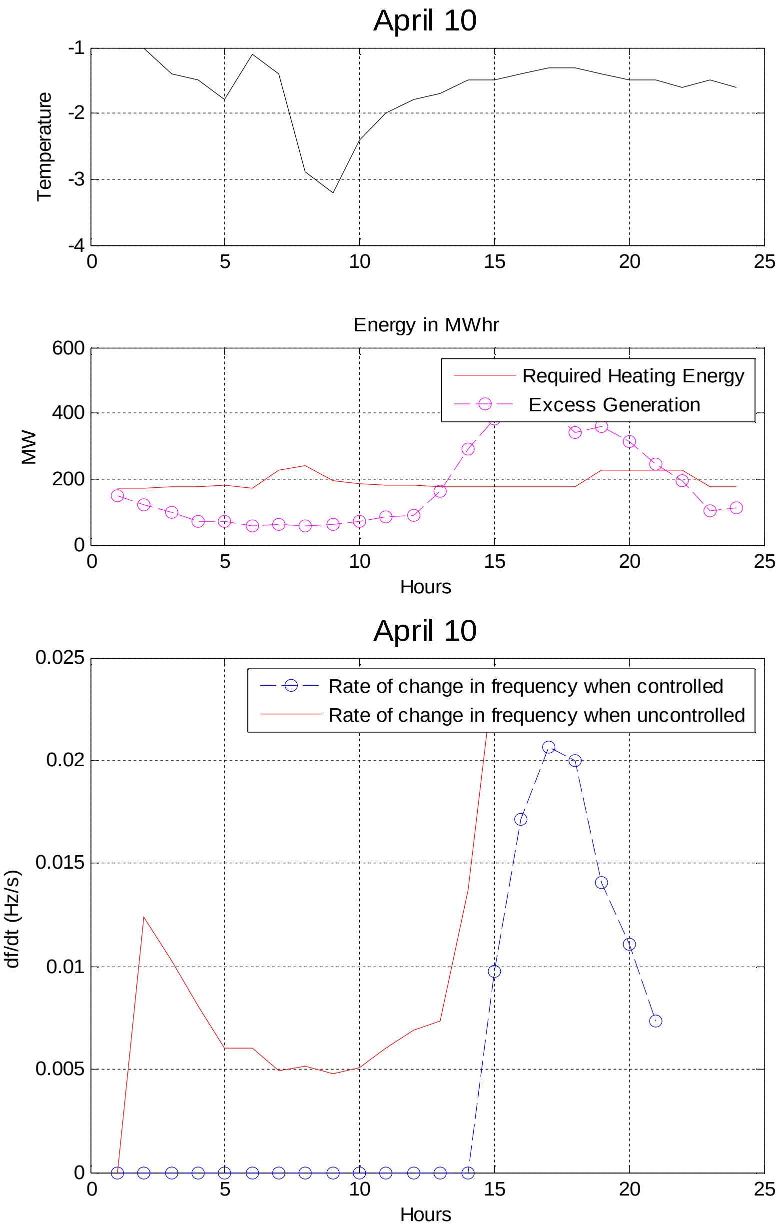


Figure 32: Frequency Control Using Heating Energy for April 10.

In this case, initially the required heating energy (H_{req}) is greater the excess generation (E_{gen}). Thus frequency can be maintained at its nominal value. After 13th hour excess generation increases rapidly and available heating energy is not enough to match it. Thus the system frequency goes on increasing and generating unit has to be tripped off before it crosses the 50.1 Hz limit.

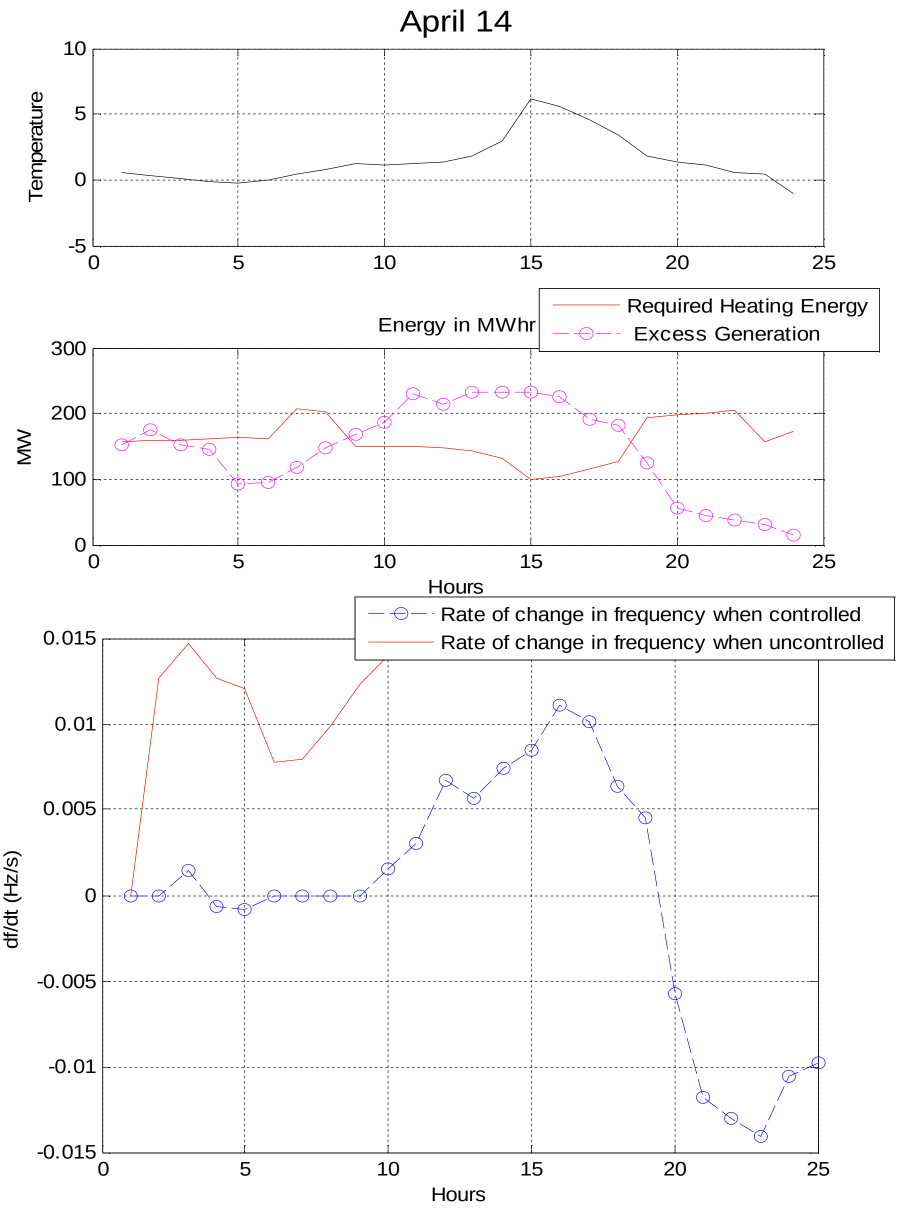


Figure 33: Frequency Control Using Heating Energy for April 14.

This case is similar to Figure 32 but frequency is controlled before it deviates from specified operational limits. Here, required heating energy (H_{req}) is initially more than the excess generation (E_{gen}). As excess generation (E_{gen}) becomes more than required heating energy (H_{req}), frequency starts to increase from that instant. But with availability of leftover heating before the system frequency reaches 50.1 Hz. Hence, the frequency is again reduced to retain its nominal value as shown in

Figure 33. The cost of storing heating energy in off peak period is € 0.0035064 per kWh per customer. During frequency control, customer has to pay € 0.0083195 per kWh. The difference between using energy during frequency control and off peak hour is € 0.0048131 kWh.

Accordingly frequency control using heating energy required for different days are shown in Figures below.

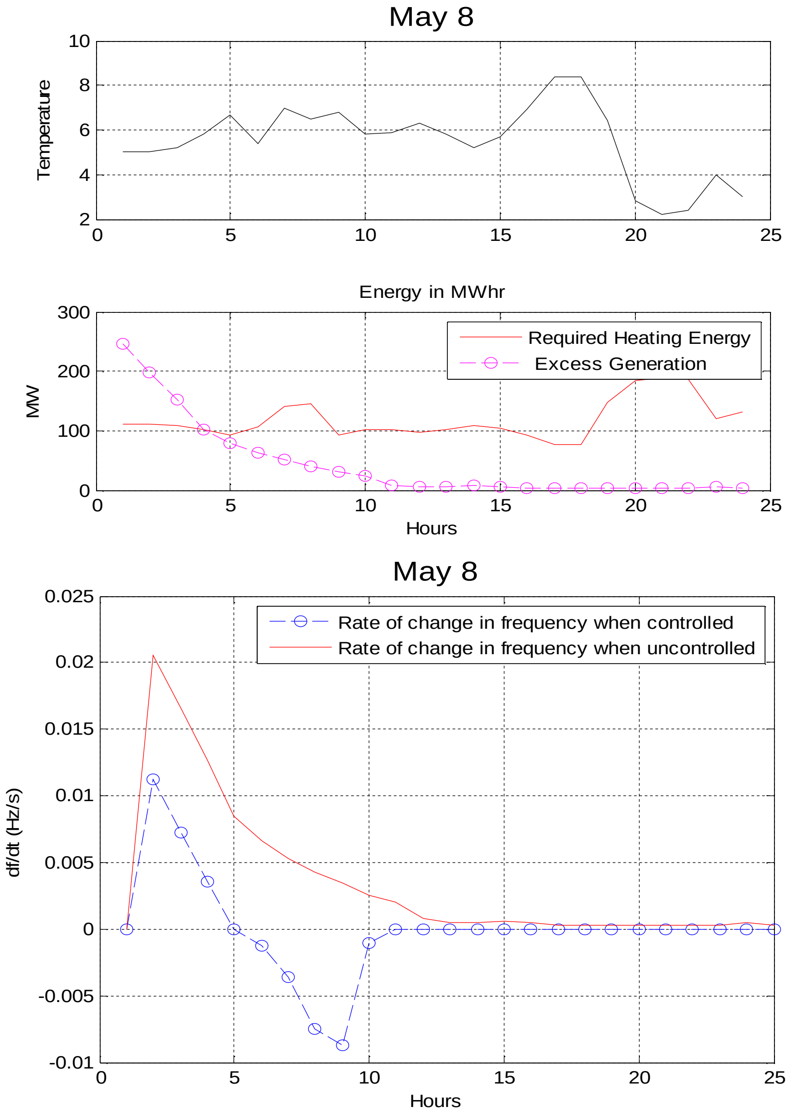


Figure 34: Frequency Control Using Heating Energy for May 8.

The cost of storing heating energy in off peak period is € 0.0031074 per kWh per customer. During frequency control customer has to pay € 0.0075261 per kWh. The difference between using energy during frequency control and off peak hour is € 0.0044187.

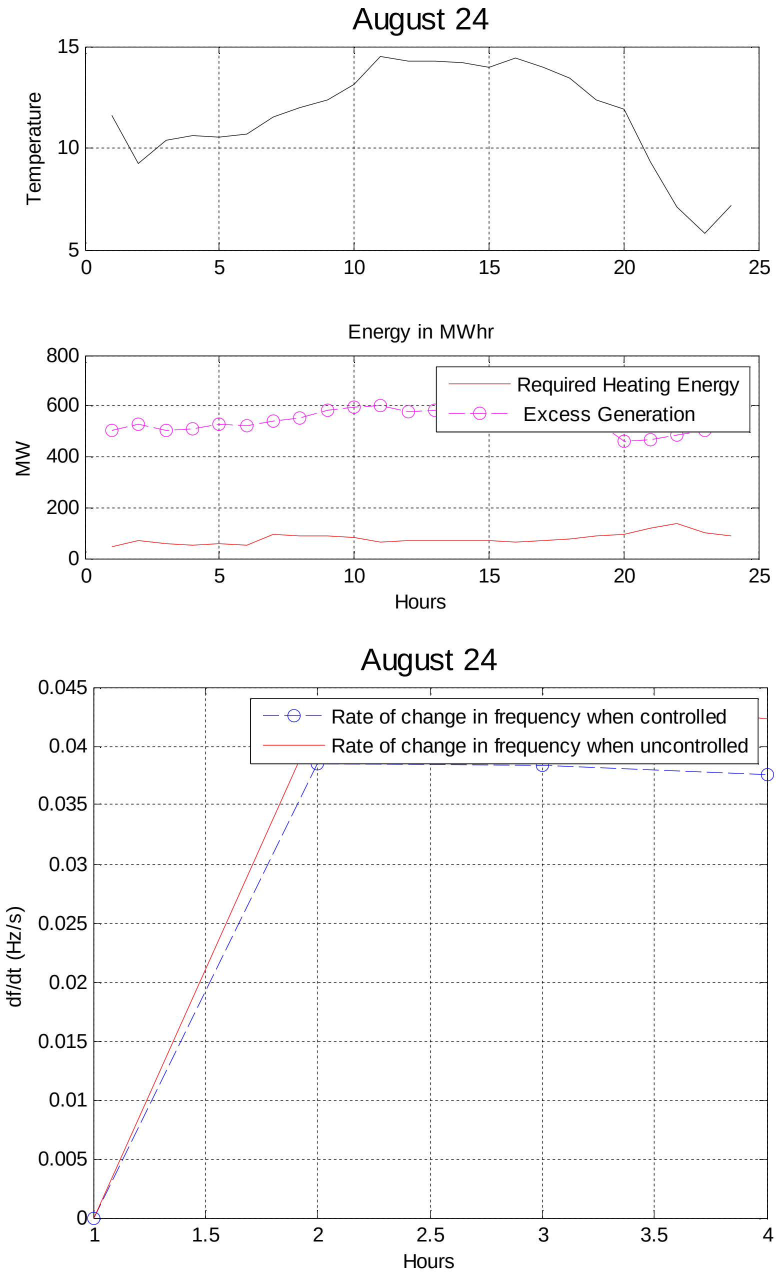


Figure 35: Frequency Control Using Heating Energy for August 8.

In this case, the excess generation is always greater than the required heating energy. Hence, system frequency cannot be maintained within the limit even with the application of the required heating energy as frequency reserve. Similar scenario can be found almost throughout the summer. Heating energy requirement is almost zero. Thus heating energy cannot provide frequency reserve.

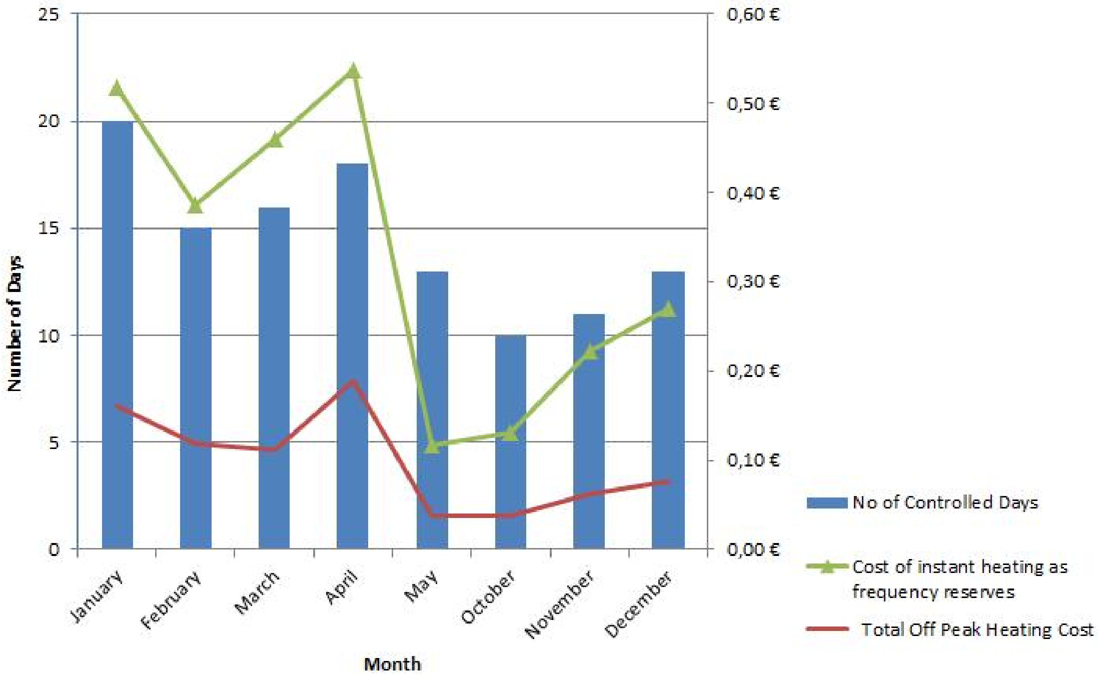


Figure 36: Summary of simulations.

Figure 36 shows the summary of simulations with treatment of required heating energy for a house as frequency control reserves. Excluding the summer period, heating energy required for a house has the potential to serve as frequency reserve for 116 days throughout the year for assumed excess generation. Simulation shows that for 20 days in January, 15 days in February, 16 days in March, and 18 days in April the over frequency problem can be mitigated. Similarly for 13 days in May, 10 days in October, 11 days in November, and 13 days in December the heating energy required for house can operate as frequency control reserves. Similarly the cost of both off peak heating and for frequency reserve has been calculated for each day. As the balanced price was considered for both period, off peak heating cost still seems to be less expensive than compared to instant heating.

CHAPTER 5

Conclusion

This thesis reviews the effect on power system frequency with variability and uncertainty associated with the power produced from renewable energy. Traditionally, the spinning reserve has been supplied from the generators during system emergency and load has been underutilized. Demand can play active role in control of power system balance. Electric loads can actually be turned on or off in response to frequency deviation observed in the power system. Thus, thesis discusses the application of frequency responsive load as spinning reserves. Thesis also studies desirable characteristics the load should possess to be used as a spinning reserve in frequency control.

Thesis studies demand response potential of heating energy required for a house via electric space heater as frequency responsive reserves. The heat loss from a house with respect to external temperature was calculated on hourly basis. So, with obtained load profile, the simulation was performed in Matlab to control the frequency for probable excess generation occurring on hourly basis throughout the year. The results has shown that 116 out of 356 days, heating energy required for the house was able to maintain the frequency with in limit. During summer the heating load are almost zero so it was not possible to control the frequency. Similarly, cost of using heating energy as frequency reserve was calculated and compared with that off peak heating. The above conclusions are based on simulation and the reported results in the literature. Experimental validation could not be done here, which is left as a future work to confirm the results from the simulations. This thesis considers only heating energy via electric space heater to be used as frequency responsive loads. Other loads such as refrigeration and compressed air, water pumping, electric vehicles charging also can be considered as frequency responsive load. Once the energy consumption of profile of these loads is known then, they can also be integrated with heating energy profile and used for frequency control.

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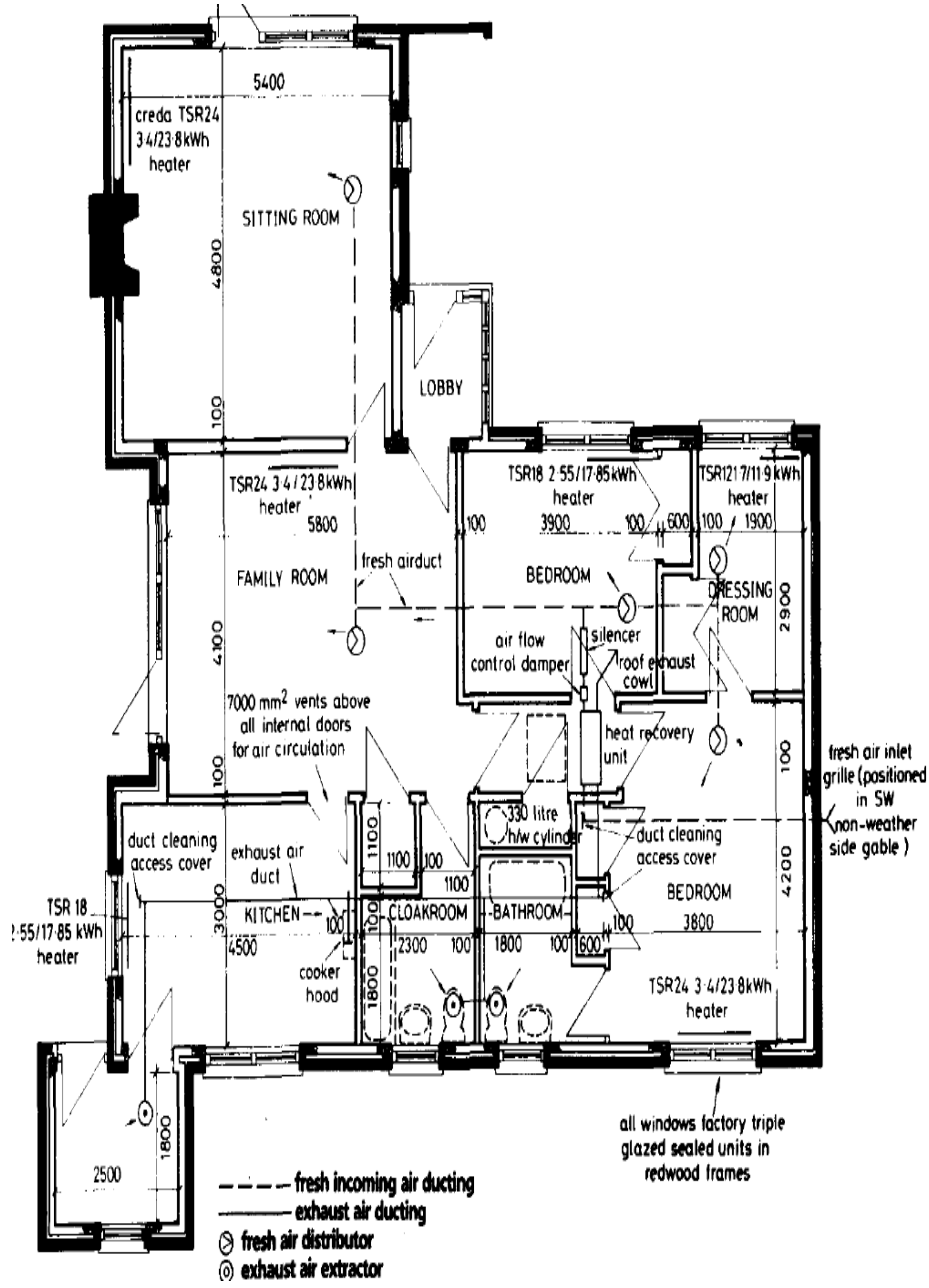
APPENDIX A

Layout of the house



Dimension of the House

Section of the Apartment	Length(m)	Breadth(m)	Area	Volume
Sitting room	5,4	4,8	25,92	63,504
Family Room	5,8	4,1	23,78	58,261
Kitchen	4,5	3	13,5	33,075
Dinning Room	2,5	1,8	4,5	11,025
Cloark Room	2,3	2,9	6,67	16,3415
Bed Room 1	3,9	2,9	12,15	29,7675
Bed Room 2			23,27	57,0115
Total Area			109,79	

Sitting room	Area
Surface Element	
External Wall 1	1,344
External Wall 2 excluding window	1,27008
Window(16% of wall)	0,24192
External Wall 3 (excluding adjacent to lobby)	0,924
External wall (adjacent to lobby)	0,21
Floor Area	25,92

Family Room	
External wall 1 including window	1,148
Window(16% of wall)	0,18368
External wall 1 excluding window	0,96432
Door to Lobby	2,52
Floor Area	23,78

Dining Room	
External wall 1 adjacent to kitchen room	0,504
External wall 2 in dinnig room	0,504
External Wall 3 in Dinning room including window	0,7
Window(16% of wall)	0,112
External Wall 3 in Dinning room excluding window	0,588
Door	0,21
Floor Area	4,5

Kitchen	
External wall 4 in the kitchen including window	0,84
Window(16% of wall)	0,1344
External wall 4 in the kitchen excluding window	0,7056
Floor Area	13,5

Bed Room1

External wall to bed room 1 including windows	1,288
Window(16% of wall)	0,20608
External wall to bed room 1 including windows	1,08192
Floor Area	12,15

Cloark Room

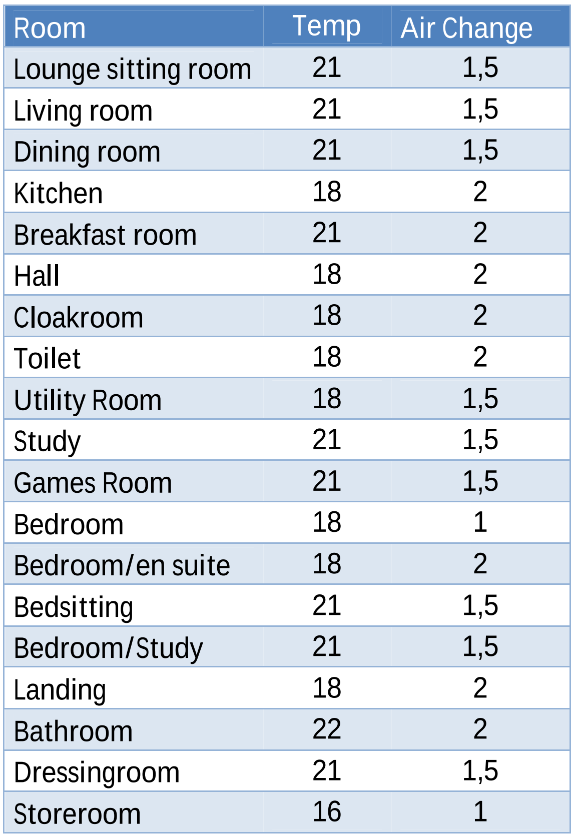
External Wall including window	0,644
Window(16% of wall)	0,10304
External Wall excluding window	0,54096
Floor Area	6,67

Bed Room 2

External wall 1	2,016
External wall 2 including windows	0,532
Window(16% of wall)	0,08512
External wall in the bathroom including window	0,504
Window of bathroom(16% of wall)	0,08064
External wall in the bathroom excluding window	0,42336
Floor Area	23,27

APPENDIX B

Values of Air Change Rate, Specific Factor of the Air



Room	Temp	Air Change
Lounge sitting room	21	1,5
Living room	21	1,5
Dining room	21	1,5
Kitchen	18	2
Breakfast room	21	2
Hall	18	2
Cloakroom	18	2
Toilet	18	2
Utility Room	18	1,5
Study	21	1,5
Games Room	21	1,5
Bedroom	18	1
Bedroom/en suite	18	2
Bedsitting	21	1,5
Bedroom/Study	21	1,5
Landing	18	2
Bathroom	22	2
Dressingroom	21	1,5
Storeroom	16	1

APPENDIX C

Matlab code for System Frequency Calculation

```
load('hrly_gen'); % Possible Excess Generation %
f0=50;           %Intial System Frequency %
w=300000  % Kinetic Energy Stored in Nordic Transmission Network,MWs%
message = 'trip off';
Excess_Genration = hrly_gen
for i=2:length(Excess_Genration)+1
    system_frequency(1)=f0;
    new_Systemfrequency=system_frequency(i-1);
   Next_HourExcess_Generation=Excess_Genration(i-1);
    const_a = new_Systemfrequency;
    system_frequency(i)=const_a +(new_gen*const_a)/(2*w);
    if system_frequency(m)>=50.1
        message
        break
    end
end
```

Matlab Code for matching Excess generation with Required Heating Energy profile and calculation of System Frequency

```
load('Required_heating_energy')% Load Required Heating Energy Data on
Hourly Basis%
load('Excess_gen');% Load Possible Excess Generation Data on Hourly
Basis%
Difference=Excess_gen-Required_heating_energy;
net_change_ofload=zeros(size(Difference));
cumusum=0;  %  Initial leftover Excess generation Injected into the
system%
previouscumusum=0; % Cumulative of leftover Excess generation
Injected into the system%
for i=1:length(Excess_energy)
    cumusum=cumusum+Excess_energy(i);
    cumusum;
    if(cumusum < 0)
        if (previouscumusum >0)
            net_change_ofload(i)=-previouscumusum;
        else
```

```
            net_change_ofload(i)=0;
        end
        cumusum = 0;
    else
        net_change_ofload(i)=Excess_energy(i);
    end
    previouscumusum=cumusum;
end

f0=50; %Initial System Frequency%
w=300000;
message = 'trip off';
new_freq=f0;
 for j = 2:length(net_change_ofload)+1
     system_frequency(1)=f0;
     new_Systemfrequency=system_frequency(j-1);
     new_net_change_ofload=net_change_ofload(j-1);
     const_a = new_Systemfrequency;
     system_frequency_tobe_maintain(j) = const_a
+(new_stable_freqload*const_a)/(2*w);
     if system_frequency_tobe_maintain(j)>=50.1
         message
         break
     end
 end
```

Balancing Excess Generation and Required Heating Energy Profile.

January 1

Hourly Possible Excess Generation(Egen)	Hourly Required Heating Energy(Hreq)	Difference Between Egen and Hreq	Net Change in Load balance(ΔP)	System Frequency
137	221,6166326	-84,6166326	0	50
168	224,6386776	-56,6386776	0	50
168	227,6607226	-59,6607226	0	50
165	233,7048126	-68,7048126	0	50
152	245,7929925	-93,7929925	0	50
127	255,8664758	-128,8664758	0	50
133	317,314724	-184,314724	0	50
116	326,3808589	-210,3808589	0	50
114	285,0795774	-171,0795774	0	50
113	292,1310157	-179,1310157	0	50
95	291,1236674	-196,1236674	0	50
107	273,9987458	-166,9987458	0	50
117	275,0060941	-158,0060941	0	50
122	288,1016224	-166,1016224	0	50
145	297,1677574	-152,1677574	0	50
152	314,292679	-162,292679	0	50
132	302,204499	-170,204499	0	50
121	298,1751057	-177,1751057	0	50
136	352,5719155	-216,5719155	0	50
135	352,5719155	-217,5719155	0	50
133	357,6086572	-224,6086572	0	50
108	369,6968371	-261,6968371	0	50
70	317,314724	-247,314724	0	50
56	328,3955556	-272,3955556	0	50

January 14

Hourly Possible Excess Generation(Egen)	Hourly Required Heating Energy(Hreq)	Difference Between Egen and Hreq	Net Change in Load balance(ΔP)	System Frequency
424	208,5211043	215,4788957	215,4788957	50,01795657
430	212,5504976	217,4495024	217,4495024	50,03608387
386	217,5872393	168,4127607	168,4127607	50,0501284
343	217,5872393	125,4127607	125,4127607	50,06058994
281	215,5725426	65,4274574	65,4274574	50,06604884
247	214,5651943	32,4348057	32,4348057	50,06875531
227	264,9326108	-37,9326108	-37,9326108	50,06558991
244	262,9179141	-18,9179141	-18,9179141	50,06401135
243	211,5431493	31,4568507	31,4568507	50,06663611
239	208,5211043	30,4788957	30,4788957	50,0691794
238	205,4990593	32,5009407	32,5009407	50,07189156
213	198,447621	14,552379	14,552379	50,073106
215	199,4549693	15,5450307	15,5450307	50,07440332
205	205,4990593	-0,4990593	-0,4990593	50,07436167
204	209,5284526	-5,5284526	-5,5284526	50,07390028
238	221,6166326	16,3833674	16,3833674	50,07526757
246	237,7342059	8,2657941	8,2657941	50,07595743
245	248,8150375	-3,8150375	-3,8150375	50,07563902
257	307,2412407	-50,2412407	-50,2412407	50,07144592
264	317,314724	-53,314724	-53,314724	50,06699668
233	340,4837355	-107,4837355	-107,4837355	50,0580277
181	351,5645672	-170,5645672	-170,5645672	50,04379749
154	322,3514656	-168,3514656	-168,3514656	50,02975591
144	326,3808589	-182,3808589	-182,3808589	50,01454846

March 18

Hourly Possible Excess Generation(Egen)	Hourly Required Heating Energy(Hreq)	Difference Between Egen and Hreq	Net Change in Load balance(ΔP)	System Frequency
242	182,3300477	59,6699523	59,6699523	50,0049725
259	182,3300477	76,6699523	76,6699523	50,01136229
278	182,3300477	95,6699523	95,6699523	50,0193366
221	183,3373961	37,6626039	37,6626039	50,02247637
159	185,3520927	-26,3520927	-26,3520927	50,02027937
123	184,3447444	-61,3447444	-61,3447444	50,01516524
132	231,6901159	-99,6901159	-99,6901159	50,00685521
175	229,6754192	-54,6754192	-54,6754192	50,0022983
204	173,2639128	30,7360872	30,7360872	50,00485976
269	166,2124745	102,7875255	102,7875255	50,01342621
268	162,1830811	105,8169189	105,8169189	50,02224666
254	155,1316428	98,8683572	98,8683572	50,03048935
265	152,1095978	112,8904022	112,8904022	50,03990262
260	156,1389912	103,8610088	103,8610088	50,04856462
220	163,1904295	56,8095705	56,8095705	50,05330335
214	168,2271711	45,7728289	45,7728289	50,05712181
162	174,2712611	-12,2712611	-12,2712611	50,05609804
194	176,2859578	17,7140422	17,7140422	50,05757587
210	238,7415542	-28,7415542	-28,7415542	50,05517798
180	249,8223858	-69,8223858	-69,8223858	50,04935303
145	251,8370825	-106,8370825	-106,8370825	50,04044115
197	263,9252625	-66,9252625	-66,9252625	50,03485953
197	233,7048126	-36,7048126	-36,7048126	50,03179867
199	249,8223858	-50,8223858	-50,8223858	50,02756077

April 14

Hourly Possible Excess Generation(Egen)	Hourly Required Heating Energy(Hreq)	Difference Between Egen and Hreq	Net Change in Load balance(ΔP)	System Frequency
152	156,1389912	-4,1389912	0	50
176	158,1536878	17,8463122	17,8463122	50,00148719
152	160,1683845	-8,1683845	-8,1683845	50,00080647
145	162,1830811	-17,1830811	-9,6779277	49,99999997
93	163,1904295	-70,1904295	0	49,99999997
95	161,1757328	-66,1757328	0	49,99999997
118	207,513756	-89,513756	0	49,99999997
148	203,4843627	-55,4843627	0	49,99999997
168	149,0875528	18,9124472	18,9124472	50,001576
186	150,0949012	35,9050988	35,9050988	50,00456819
230	149,0875528	80,9124472	80,9124472	50,01131151
215	147,0728562	67,9271438	67,9271438	50,01697339
232	143,0434629	88,9565371	88,9565371	50,02438895
233	130,9552829	102,0447171	102,0447171	50,03289682
232	98,72013634	133,2798637	133,2798637	50,04401078
226	104,7642263	121,2357737	121,2357737	50,05412266
191	114,8377096	76,1622904	76,1622904	50,06047639
181	126,9258896	54,0741104	54,0741104	50,06498801
125	193,4108794	-68,4108794	-68,4108794	50,0592797
57	198,447621	-141,447621	-141,447621	50,04747842
44	200,4623177	-156,4623177	-156,4623177	50,03442751
37	205,4990593	-168,4990593	-168,4990593	50,02037625
30	157,1463395	-127,1463395	-127,1463395	50,00977641
15	172,2565644	-157,2565644	-117,4442125	49,99998748