Ørsted·DTU
Technical University of Denmark

Catarina Marcus-Møller (s011285)

Demand as frequency controlled reserve

- Analysis of technology and potentials

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Demand as frequency controlled reserve – Analysis of technology and potential

Rapporten er udarbejdet af:
Catarina Marcus-Møller (s011285)

Vejleder(e):
Jacob Østergaard, Ørsted DTU
Mikael Togeby, Ea Energianalyse

Ørsted•DTU
Center for Elteknologi (CET)
Danmarks Tekniske Universitet
Elektrovej
Bygning 325
2800 Kgs. Lyngby
Denmark

www.oersted.dtu.dk/cet
Tel: (+45) 45 25 35 00
Fax: (+45) 45 88 61 11
E-mail: cet@oersted.dtu.dk

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Abstract

Reserves are needed in the electricity system. Today reserves are delivered by generation, but it might be beneficial also to use electricity demand. This report investigates different household technologies and their use as frequency controlled reserve (DFR). The investigated technologies are: refrigerators, freezers, air conditioners, electric floor heating, electric water heating, washing machines and tumble dryers. The four best technologies for DFR are electric water heaters, electric floor heating, refrigerators and freezers. In East Denmark the demand in the investigated technologies are able to deliver 25 MW of DFR at all times of the year. To make DFR possible for the technologies a frequency control device is needed. The technology for the DFR option already exists and will be launched in the Danish market in the beginning of 2007.

Three Danish companies were used as cases to make the preliminary analysis of industrial demands as DFR. The three companies could supply minimum 3.4 MW of DFR at all most all times of the year.

The price for the 25 MW of reserves delivered by the demands in households and industry in East Denmark is, in the cheapest example, 9 million DKK/year, this is comparable to price of traditional reserves.

1 Preface

This report is part of a project concerning demand as frequency controlled reserve (DFR), made in co-operation between Ea Energianalyse and Ørsted.DTU.

The report is written as a Special course at Ørsted DTU in the summer and fall of 2006. The project represents 15 ects-points.

Jacob Østergaard, Ørsted DTU, has been supervisor of this project. Mikael Togeby, Ea Energianalyse, has been external supervisor. I thank them both for counselling and guidance throughout the project.

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3 Introduction

In the electric power system the production and demand should be in balance at all times. The balance in the power system is obtained by controlling the frequency. If there is too much production in a power system the frequency will be too high and vice versa. Today regulation of frequency is made in the central power plants; the production is regulated according to the frequency.

Since production and demand are dependant in the power system, disconnecting selected demands will have the same effect as raising the production. This is the point of demand as frequency controlled reserve (DFR). If demands are disconnected as DFR it is of course important that the consumers and industrial consumers are not bothered or harmed by the disconnections of the different appliances.

This report investigates the technical possibilities of using demand as reserve in the power system, replacing some of the reserves given by the production capacity of the central power plants.

Many different appliances in household, commerce and service and industry consume electricity. All these different types of demand are not equally useful as DFR. This report analyses different technologies and their use as DFR. The following aspects will be examined for each technology:

<u>Usage</u>: When does the appliance use electricity? Does the consumer influence the demand of the appliance?
<u>Potential</u>: Is there enough demand in this type of appliances to influence the frequency by disconnections?
<u>Technical possibilities for disconnections</u>
<u>Start-stop problems</u>: Technical options for reconnection
<u>Wearing parts</u>: Will parts in the unit that will wear out if the unit is switched on and off?
<u>Electronic contents</u>: Does the appliance contain electronic controls needed for DFR?
<u>Technology status</u>: Is DFR an option at this point of time?

The electricity consuming appliances analysed in this report is seen below, the technologies are listed in no order of priority:

Household appliances
- Refrigerators
- Freezers
- Air conditioners
- Electric floor heating
- Electric water heating
- Washing machines / tumble dryers

Industrial demands
- Cold stores
- Air conditioners

Industrial cases
- Water purifying plant – Lynetten
- Hospital – Rigshospitalet
- UPS-systems – BaneDanmark

Frequency relay
- Tell-it-Online

4 Background

4.1 Reserves in the Danish Power systems

The electric power system in Denmark is separated in two systems. The system in Jutland and Funen is connected to the German and European system UCTE and the system in Zealand is connected to Sweden and the Nordel system, the Zealand system is called the East Danish system. The East Danish system is also connected to Germany by a DC connection, the frequency of the two systems are not coherent. Both in UCTE and Nordel the frequency is kept within a normal band of 50 Hz +/-0.1 Hz.

In this report the East Danish system is used as an example and this system will be described more thoroughly in the following.

In the east Danish system there are three types of reserve: frequency controlled normal operations reserve, frequency controlled disturbance reserve and manually controlled disturbance reserve. The two frequency controlled reserve types at activated automatically.

The normal operations frequency controlled reserve is active in the frequency range from 49.9 to 50.1 Hz, and the regulation is proportional. This means the reserves will be activated proportional with the distance to the wanted frequency.

The frequency controlled disturbance reserve operates in the frequency range from 49.9 to 49.5 Hz. The disturbance reserves react proportionally to the distance to 49.9 Hz.

In East Denmark the required amount of frequency controlled disturbance reserve is 100 MW in the East Danish system. 25 % equalling 25 MW of this amount will be attempted covered by the demand in this report. The requirement for normal operations reserves are 25 MW. (Elkraft, 2004).

The manually controlled reserves are used in situations with unbalance between plan and reality or in fault situations. The manual reserves have to react within 15 minutes. Since theses reserves are active after 15 minutes the longest disconnection period for the demand will be 15 minutes, but shorter disconnection periods are also possible.

Replacing the present reserves at the power plants with the demand is interesting because the regulation on the power plants is slower and maybe more expensive than the reserves the demand can offer.

The power plants are big dynamic units and it takes time to regulate the production on the plants. The regulation can be made by adding more fuel to the boiler, or by letting more or less steam through the turbines. Adding more fuel to the boiler will not effect the production instantaneously because of the thermal inertia in the boiler. It will take some time before a raise in fuel consumption will be seen in the production. Letting more or less steam through the turbines will have an effect more quickly than adding fuel, since the steam is already produced and opening or closing valves will happen very quickly.

The effect on the frequency of disconnecting demand is instantaneous, if it is technically possible to disconnect certain types of demand instantaneously without damaging the equipment.

The power plants can have a production lower than their maximal production to ensure the capacity to regulate the production if more production is needed. Setting production capacity a side for regulation costs the power plants the loss of production and if the electricity price is high the lost earnings will big.

If there is no damage on the equipment and no inconvenience for the consumer the demand as frequency controlled reserve can be cheaper than the regulation possibility on the power plants. The installation cost of the frequency control possibility is the only cost for the demand as reserve. If the consumer is paid for letting the frequency control their demand this cost is added to the total cost for DFR. The TSO (Transmission System Operator) buys the reserves from the power plants, they could buy it from the consumer instead.

The demand is firstly thought to be used as disturbance reserve, but some technologies might be usable for normal operations reserve. The use of demand as normal reserve could relive the power plants of some of the pressure from the normal reserve, letting the power plants have a stable production instead of changing the production a bit at all times.

The amount of automatic, or frequency controlled, reserves in the power plants when the frequency is low has been sketched and is seen in Figure 1.

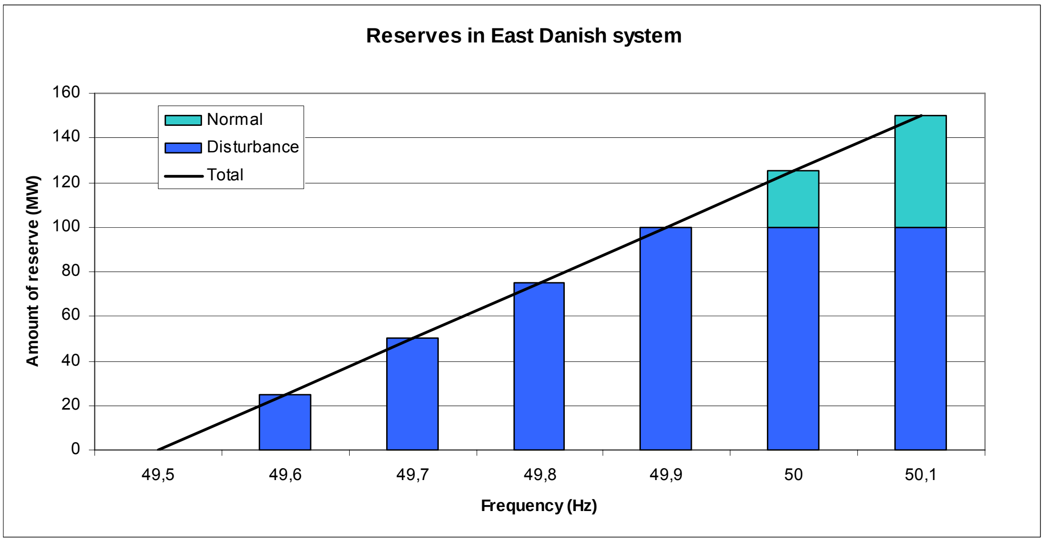

Figure 1 Amount of automatic reserves as a function of frequency.

As seen in Figure 1 the amount of reserves falls as the frequency falls. The fall in amount of reserves is caused by the proportional operations of reserves in the power system. If a frequency of 49.9 Hz is detected in the system the disturbance reserves will start reacting, 25 % of the reserve amount will start. If then a frequency of 49.8 Hz the first 25 % of the frequency controlled disturbance reserve is already in operation leaving 75 % of the reserve ready to react. In fault situations the system has a better starting point if the frequency is high. If a fault happens when the system frequency is 50.0 the amount of automatic reserves are 125 MW. If a fault happens at 49.6 the amount of automatic reserves are 25 MW. If demand is used as reserve there will be less regulation in the power plants, this should enforce the stability of the power system.

In this report the use of DFR is investigated for under frequencies, situations with too much demand. In cases with over frequencies some demands could be connected to the system to lower the frequency, but this is not investigated in this report.

4.2 The frequency in the system now

To see if there is a need for the demand as frequency controlled reserve some historic frequency data has been analysed in the overall project. Some examples of the frequency are show in the following.

The duration of the under frequencies is interesting because it sets how long the demand has to be disconnected. The duration of under frequencies can be seen in Table 1, the data is from a 5 month period of 2005.

Table 1 Duration of under frequencies in the Nordel system. The data is made by Energinet.dk and is 10 sec measurements for 5 months of 2005.

Frequency (Hz)	Events per month	Average duration	Max duration
< 50.00	14,300	91 sec	4 hours
< 49.95	6,500	38 sec	44 min.
< 49.90	454	25 sec	13 min.
< 49.85	4.8	17 sec	2 min.
< 49.80	2.6	11 sec	20 sec

If the demand is used as disturbance reserve there are 454 events per month where the frequency is lower than 49.90, below the normal frequencies, see Table 1. The average duration of these events has been 25 seconds, and the maximal duration was 13 minutes. The 15 minute maximum duration of disconnection is not reached in the five months, all the under frequencies have shorter duration. The difference in the average and the max duration indicate few long under frequencies, in fact only 10 % of the events have longer durations than 3 minutes.

Frequencies lower 49.85 occurs 4.8 times a month and of these only 2.6 has frequencies under 49.80. There are not many under frequencies below 49.85 and the frequency band where the demand could be used as reserve would mostly be from 49.90 to 49.85.

Disconnections of demands will seldom have duration of 15 minutes, the disconnection will be shorter. The strain on some of the demand technologies will be smaller the shorter the disconnection.

Since different demands are used at different times of the day or year, the point of time for the under frequencies are interesting when investigating the possibilities of DFR. The under frequency occurrence as a function of the minute number in the hour is seen in Figure 2.

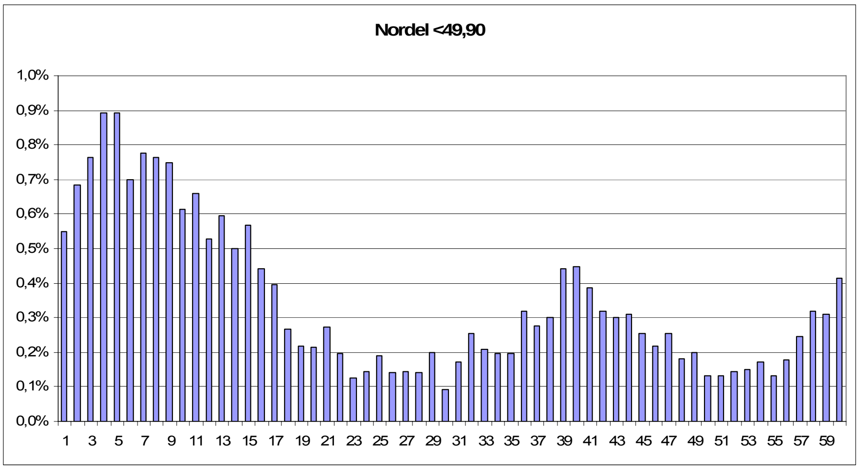

Figure 2 The probability of under frequencies in the Nordel system as a function of the minute number. The probability is calculated from five months of 10 second data from Energinet.dk.

The probability of under frequencies is highest in the beginning of the hour. Within the first 15 minutes of the hour the probability of under frequencies is higher than in the rest of the hour, see Figure 2. This dependency of the under frequencies to the beginning of the hour, is probably inflicted by the structure of the electricity market in the Nordel system. The market changes every hour, meaning the electricity price and the production change every hour. Changes in production are therefore made around the hour shifts causing the system to be less stable in the beginning of the hour. More under and over frequencies have been detected, since the market structure has been introduced in 2001, see Figure 3.

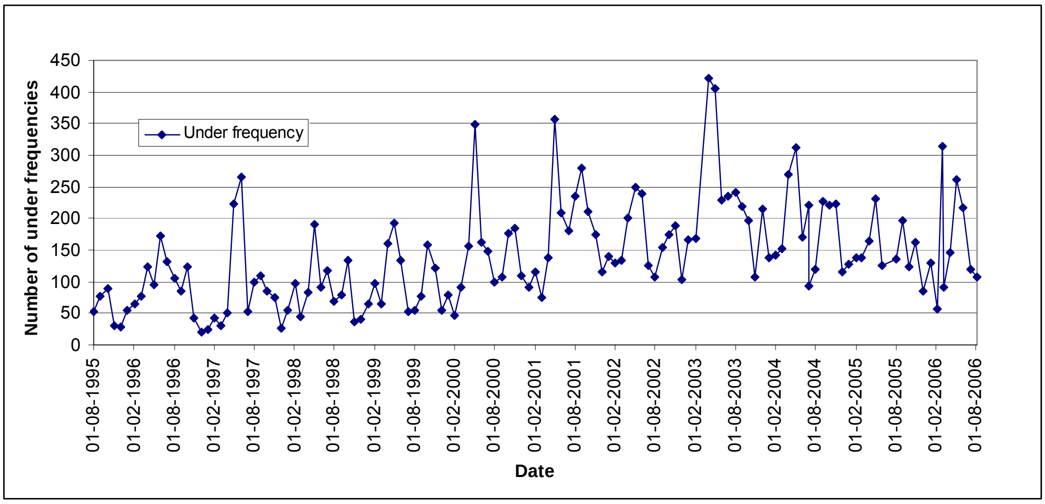

Figure 3 The number of under frequencies from 1995 to the middle of 2006. The data has been provided by Svenska Kraftnätt.

As seen in Figure 3 the number of under frequencies has double since the market structure was introduced in 2001. The instabilities in the power systems is manmade, DFR could stable the power system.

4.3 Frequency control

To make the frequency control possible electronic equipment and programming are needed. In the following the unit for frequency control will be called a frequency control device.

The frequency control device must be able to measure the frequency in the electricity grid and disconnect the different appliances.

The device can be internal and external. Internal devices can combine the frequency measurement with measurements in the appliance. For instance in a refrigerator the devices could measure the temperature inside the refrigerator, only letting the frequency disconnect the refrigerator when the temperature inside is low enough. External devices will have no communications from the appliance. For all of the investigated technologies a proposal for the requirements for the frequency control device is made.

The frequency control devices could communicate with the TSO getting disconnection and reconnection commands. There are some advantages both with and without communications. In this report, devices with no communications with the TSO have been investigated. The DFR appliances will react automatically and independently.

With no communications to the TSO it is more difficult to organize the reserves ensuring the stability of the power system. Planning the reserves in the demand can be difficult.

For some electric appliances the planning can simply be done by counting the number of demands with the frequency control possibility, adding up their amount of demand. This will give a good estimate of the reserves at the demand site. If only some of the demand disconnects at an under frequency, the total number appliances must be subtracted a percentage of the sum to get a better estimate of the reserves at the demand site.

Other demands have so varying consumption that the counting method will not be accurate e.g. washing machines.

When the DFR is used in a power system there could still be need for some reserve capacity in the power plants, since this is the way for the power companies to control the electricity the power grid. But the amount of power plant reserve can be smaller.

If the demand is used as normal reserve the power plants do not have to regulate their production when the frequency is within the normal range. Some demands will be useful as normal reserve but this is not the main focus of this report.

Reconnecting disconnected demands also has some difficulties. If all the disconnected appliances are reconnected at the same time the power system can suffer a new frequency drop. Some of the ideas to handle the reconnections are to equip the frequency control devices with a random factor. This means that when the frequency measuring device in a disconnected appliance measures a normal frequency it reconnects after a random time delay, or the reconnection frequency can be set randomly, making the reconnection point random for the different equipment.

Some appliances have a very large starting current just when the appliance is started. If all the disconnected appliances are reconnected at the same time all the starting currents will appear at the same time, resulting in an enormous amount of demand for a short time. This enormous current could trigger some of the fault relays in the power system resulting in even more problems than the previous under frequency. At least the appliances with high starting currents need a random reconnection manner to ensure there reconnection will not result in a new fault situation. The starting currents would be randomly distributed in the first couple of minutes after the normal frequency has been obtained.

4.4 Paying for DFR

If private consumers or commercial firms let the frequency control their electricity demands it could be considered to pay them for the inconvenience. There are many different ways of structuring this payment and some of them will be outlined in the following.

In private households two methods of paying the costumer are the most interesting.

The first one is to give the consumer a financial supplement if they buy an appliance with the frequency control option. The supplement should cover the installation costs of the frequency control device and a little more to pay the consumer for the inconvenience. This is a very direct way of paying the costumer and the use of the frequency control reserve possibility is not considered in this payment methods.

In the second paying method the consumer is to be paid for the amount of reserve their appliances are able to deliver. The payment could be based on the amount of demand with the possibility of DFR. The payment rate the can vary but this will not be discussed in this report. This way of paying the consumer is more complicated and requires measurements of the demand in the household. This will require more administration from the TSO buying the reserve from the consumer.

The first method is simpler than the second, but the question is which one would attract more consumers. Many people could be attracted by the financial supplement but if the consumer is interested in their electricity consumption, it is thinkable that they would find it interesting to be able monitor when and how often their demand is used as reserves. In the starting period of using the demand as DFR it could be the best idea to make the payment method as simple as possible, this means choosing the first payment method. Later the second payment method could be interesting.

In the commercial sector the same payment methods as for private households can be used. But in the production industry the firm should not only be paid for the amount of reserve they can deliver, but also for the loss of production disconnections could cause.

DFR in commercial firms will be more difficult as the commercial firms do not want to lose money if demands are disconnected. Contracts have to be formulated between firms and TSO to confirm the agreements between the two. Making contracts between the TSO and commercial firms could cause more administrative work for the TSO.

5 Choice of demand technologies

In this chapter some preliminary analyses of usage and potential will lead to a choice of the technologies that will be included in the analysis in the rest of this report.

5.1 Usage

The usage of the different technologies are analysed to ensure that if frequency control is made available to the technology there will be a consumption and thereby a potential for DFR. It will be cheaper to make frequency control available for technologies that consume electricity for a long period of time, than in a technology that are used for short periods. Technologies with consumption for longer periods are more connected to the grid and thereby offer their demand for DFR for longer periods than technologies with consumption in short periods.

Also the consumers' influence on the demand of the technology is interesting, because if the consumer influences the demand a lot the loss of comfort is more likely than in technologies where the consumer do not influence the demand.

Refrigerators and freezers are analysed in the following potential analysis. Refrigerators are connected to the grid at all times and they have consumption at all times of day and all periods of the year.

Electric spaces heating are also included in the analysis. Electric space heating are used mostly in the heating period, in Denmark this means from approximately October to May. But other than the seasonal variation the consumer only influence the use of the electric heating by setting a wanted temperature.

Also electric water heating are analysed. The consumption of hot water varies during the day in private household. Most hot water is consumed in the mornings and evening and not much during the night. But the electric water heaters have some consumption in all hours, to keep the temperature in the water heater at a preset temperature; the temperature of the water will fall due to the heat loss from the water heater.

The demand in washing machines, dishwashers and tumble dryers are very dependent on the consumer, since they only consume electricity when they wash or dry cloths. But even though this is the case most consumers are not bothered if the cloths or dishes are delayed for 15 minutes. Some consumers want the cloths or dishes ready at a certain point of time and this could be taken into account when the frequency control device is design. A timing option for the consumer, could allow the appliance to disconnect if the washing or drying program can be finished before the selected time.

Coffeemakers are often mentioned in the discussion about DFR because it is a demand that can be disconnected without causing the consumer too much loss of comfort. Therefore they are included in the preliminary potential analysis, to see if the consumption in coffeemakers can be seen in comparison with other consumptions. But the usage of coffeemakers is about and hour a day and this is a very short period of time.

Other cooking appliances will not be analysed, since the electricity demand for cooking is very influenced by the consumer. Disconnections, of for instance the stove, will very likely happen in a bad time. Maybe the disconnections will not harm the food, but it can bother or irritate the consumer.

The consumption in television, stereos and computers are also not included in the analysis, since the consumption in these devices is very dependant on the consumer. All consumers would be bothered if the TV was turned off in the middle of a program. Of cause the standby consumptions in these devises could be disconnected but these consumption are not included in the analysis. As exception in these types of demand laptops can be mentioned. Since laptops contain batteries they can be disconnected from the electricity grid in short periods without bothering the consumer, but they are not included in this analysis.

5.2 Potential

The potential of the different technologies are analysed to ensure that if frequency control is installed the disconnection of the technology would have and effect on the frequency. If a technology has too little demand it would be too expensive to make frequency control for this technology.

In the potential analysis the number of appliances in East Denmark is based on a Danish study called ELMODEL-bolig. In this study the number of appliances in households all over Denmark is estimated on the basis of a questionnaire survey. The questionnaires are answered by consumers in ca. 2,000 households all over Denmark. The survey are made every second year, the newest results are from 2004. (http://www.elmodelbolig.dk/)

The potential is calculated using an average yearly consumption, calculated from the average consumption of new equipment and ten year old equipment. By using the consumption of new and ten year old equipment, the real consumption in all East Danish equipment is simulated. The average consumption is for normal use of the appliance and in the calculations the consumption is set to be the same is all hours of the year. (http://www.enervice.dk/Default.asp?ID=29, d. 13-10-2006)

The results from the calculations on the total consumption of the selected technologies in eastern Denmark can be seen below.

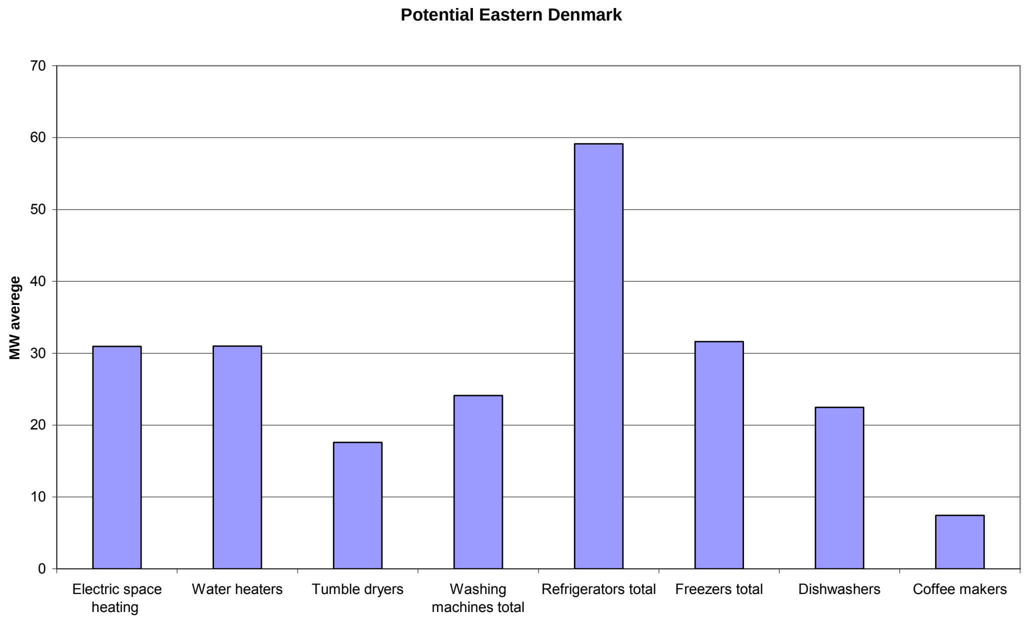

Figure 4 The average electricity consumption in different household devices in East Denmark.

In Figure 4 electric space heating includes both household with only electric space heating and households with partial space heating, e.g. floor heating in bathrooms. The refrigerator category covers: fridge freezers, refrigerators with freezing compartment and standalone refrigerators. Freezers include both chest and upright standalone freezers.

As seen in Figure 4 the biggest electricity consumption is in refrigerators. Freezers, electric space and water heating have almost the same consumption and this is the second highest consumption. Dishwashers and washing machines have the same consumption which is the third highest. The consumption in coffeemakers is lowest of the selected technologies but it is actually visible with a little more than a third of the consumption in the tumble dryers.

In the technologies with the three highest consumptions: refrigerators, freezers and electric space heating the consumer have little influence on the demand. These three demands are included in the following analysis.

Electric water heating have large electricity consumption in periods with high hot water consumption but also in periods without hot water consumption the water heater have some demand to compensate for the heat loss from the water heater. The demand of a water heater is distributed evenly all through the day and the year. Water heaters are also included in the analysis.

There is a big electricity consumption in washing machines, tumble dryers and dishwashers, but the electricity consumption of these devices are very much influenced by the consumer. Washing machines and tumble dryers are included in the analyses as an example of this type of demand that is very dependant on the consumer.

Coffeemakers are not included in the analysis since the consumption is too little and the usage is limited to less than one hour a day.

6 Refrigerators

The electricity consumption of refrigerators in East Denmark is very big, see section 5.2 "Potential". Therefore there is a big potential in using refrigerators as reserve in the power system.

In the 1,131,000 East Danish households 66 % own a fridge freezer, 60.9 % own a separate refrigerator and 19 % own a refrigerator containing a freezing compartment (http://www.elmodelbolig.dk/). This gives a total number of refrigerators in East Danish households of: 1,533,000. Based on the average yearly consumption, the East Danish refrigerators have a consumption of 518 GWh/y, corresponding to 59.1 MW on average.

6.1 The technical description

The electricity consuming unit in a refrigerator is a compressor. The compressor drives the refrigeration cycle, which is illustrated in Figure 5 and described in the following.

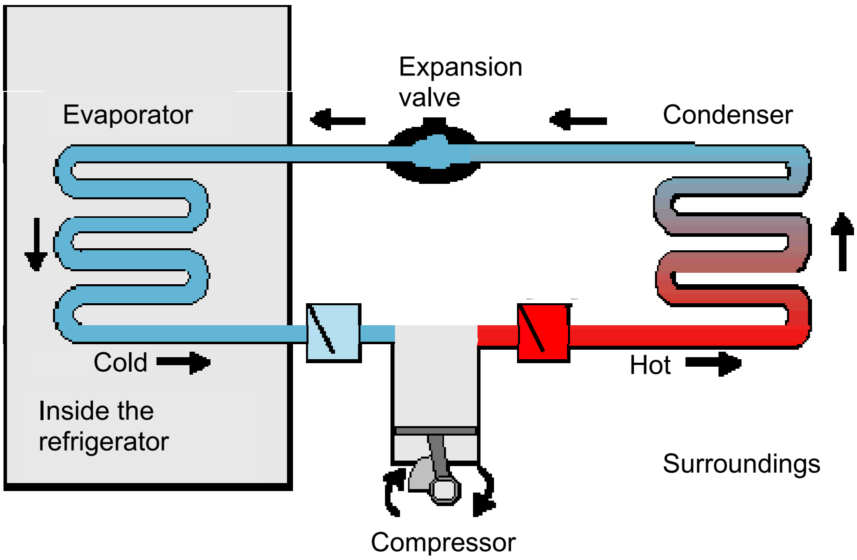

Figure 5 A drawing of the cooling system in a refrigerator.
(http://www.fipnet.gymfag.dk/kulde/koeleskab/index.htm, 18-09-2006)

As illustrated in Figure 5 the compressor, the condenser and the expansion valve are placed on the back of the refrigerator and the evaporator is placed inside the refrigerator.

At the inlet of the compressor the refrigerant is a low pressure cold gas. In the compressor the gas is compressed and the pressure and the temperature of the gas are raised. The high pressure hot gas is led to the condenser.

In the condenser the gas is cooled by the surrounding air. The cooling causes the gas to condensate to a high pressure liquid. The high pressure liquid is led to the expansion valve.

In the expansion valve the pressure of the liquid is lowered. The pressure drop also lowers the temperature of the liquid to a level that is colder than the inside of the refrigerator. The low pressure low temperature liquid is led to the evaporator.

In the evaporator the liquid is heated by the inside of the refrigerator. The heat evaporates the liquid resulting in a low pressure low temperature gas. The energy for the evaporator is taken from the air and the contents of the refrigerator and the inside of the refrigerator is thereby cooled. The low pressure low temperature gas is led back to the compressor and the cycle starts again.

The cycle moves energy in the form of heat from the inside of the refrigerator to the outside of the refrigerator.

The same technology is used in freezers and air conditioners. The properties of the refrigerant, i.e. boiling and melting point at different pressures, set the range of the cooling abilities. The boiling point of the refrigerant must be lower than the temperature of the subject that needs to be cooled.

In a refrigerator the compressor of the refrigerant cycle is controlled by a thermostat inside the refrigerator. When the temperature in the refrigerator is too high, the compressor is started, and when the temperature in the refrigerator reaches a preset lower temperature, the compressor is stopped. The compressor is started and stopped continuously during normal operations.

6.2 Power consumption

A refrigerator consumes electricity when the compressor is turned on. If the refrigerator contains electronic equipment, it will consume power at all times, but the biggest consumption of electricity is for driving the compressor.

Figure 6 shows the instantaneous value of the current in a single household refrigerator for two hours during normal use. The measurements were made by students at DTU in the fall of 2004. The measurements were made every 10 seconds for about two hours.

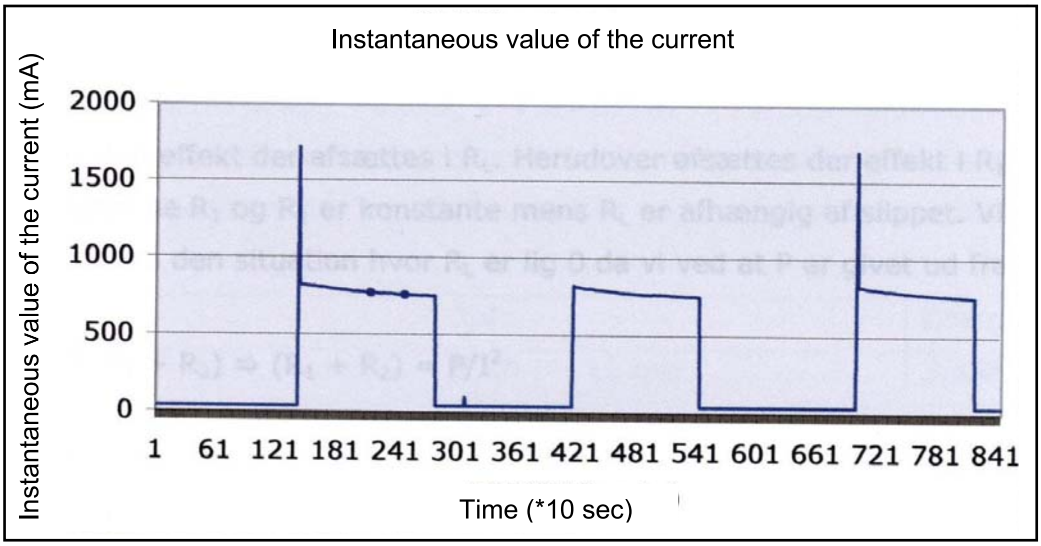

Figure 6 The instantaneous value of the current in a household refrigerator.
(Johansen, Rasmussen & Trier, 2004: 11)

As it can be seen from the graph in Figure 6 the current in the refrigerator is low for some periods and higher in some periods. The three periods with high consumption are when the compressor is turn on. The compressor is turned off when the consumption is close to zero. During the little more than two hours the compressor is switched on and off three times, this shows the start-stop behaviour of normal operations of the refrigerator.

The peaks on the first and the third consumption periods is the starting current. The compressor is driven by an asynchronous motor, this type of motor has a starting current much higher than the operating current. The starting current is a very high power consumption for a very short period of time. After the starting current the power consumption will settle on a lower level, slowly falling till the compressor is turned off. (Interview with Esben Larsen, 05-09-2006) and (Atlason et al., 2004 & Johansen et al. 2004)

The measurement is made every 10 seconds and this is why the stating current is not visible on the second consumption period on the graph in Figure 6. The starting current last shorter than 10 seconds and the second time the compressor is started it is not measured. In reality there is a starting current every time the compressor is started.

All cooling systems is characterised by a COP-value. The COP (Coefficient of performance) is the ratio between the amount of cooling and the electricity consumption. For a normal refrigerators and freezers the COPs are between 1 and 5, in the calculation of the potential a COP of 3 has been used as an example.

6.3 The use as DFR

The start-stop behaviour of normal operations of the compressor indicates that refrigerators could be used as reserves. The compressor is used to being turned on and off, it should not damage the compressor, if the frequency sometimes controls the stop of it.

Therefore refrigerators are investigated in this report. The following is based on a telephone interview and mailing correspondence with Søren Hansen from Danfoss, a Danish producer of compressor for cooling systems.

A household refrigerator can bet turned off immediately, with out damaging the equipment.

When the compressor has been turned off it cannot be started again immediately. The pressure on the piston in the compressor will be too high, and pressure equalisation is needed before the compressor can be started. If the compressor is attempted started before the pressure equalisation is finished there will be to high pressure on the piston. In some instants the compressor will not be able to start causing the compressor to seize up. If the compressor is started it will wear the compressor much more than normal operations. This wear lower the lifetime of the refrigerator drastically and this is of course not the point of using demand as frequency controlled reserve.

This problem could be handled in two ways. One way is by installing a time delay alongside the frequency measuring device. The time delay should not allow the compressor to start before the pressure equalisation is finished. The pressure equalisation takes 5-10 minutes. Such a delay is found in some refrigerators to make sure the compressor will not start if the refrigerator by accident is switched off while the compressor is running.

The other way is to install an extra valve after the compressor in the cooling system. The valve should open and make instantaneous pressure equalisation if the compressor is turned off by the frequency measurement, then the refrigerator could be turned on right after it has been stopped. If the pressure equalisation is done instantaneously by this valve, the energy the compressor put into the high pressure will be lost. The high pressure would normally be used in the refrigerant cycle, as the high pressure liquid passes the expansion valve.

The refrigerators is controlled by a thermostat switching the compressor on and off according to the cooling demand of the inside of the refrigerator.

Ordinary household refrigerators contain no electronics, in some new refrigerators with ice cube makers etc. there is some electronics. But when electronics is installed in a refrigerator there will be a constant electricity consumption in the electronics. This constant consumption can be about 10 % of the total consumption of the refrigerator. Installing electronic equipment in refrigerators will raise the electricity consumption and is not entirely preferable.

Some new refrigerators and other domestic appliances have electronic displays, monitoring e.g. the time or the temperature of a refrigerator. These types of electronics have some consumption at all times.

There are some technical problems in using refrigerators as frequency controlled reserve, but they can be solved in the designing of the frequency control deviceS.

If refrigerators are to be used for DFR it must be possible to predict the consumption of the refrigerators. As it was seen in Figure 6 the consumption of a refrigerator varies a lot. A refrigerator switches between low consumption and high consumption according to the cooling demand. But if more refrigerators are connected to the same electricity system, the total demand will even out.

In an American study was made in 1994 the electricity consumption in 10 household was metered. Results from the metering of the refrigerators in the households are seen below. The publication of the study can be found in: http://www.fsec.ucf.edu/bldg/pubs/pf300/index.htm.

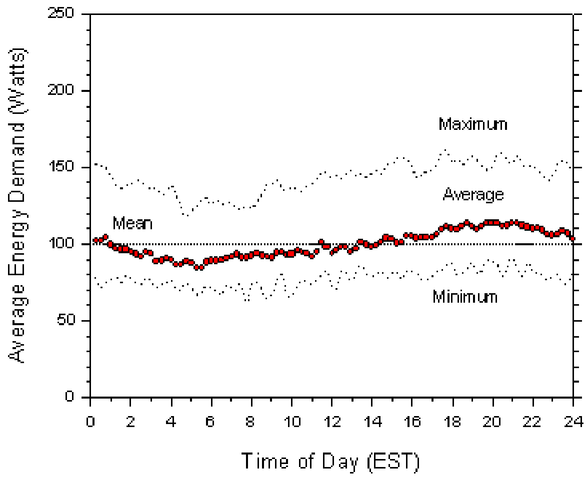

Figure 7 Daily load profiles of 10 refrigerators for a year.
(http://www.fsec.ucf.edu/bldg/pubs/pf300/index.htm, 28-10-2006)

The results in Figure 7 are made for a year for the ten refrigerators; this is the same as for one day for 3,650 refrigerators. As seen not all 3,650 refrigerators is turn off at the same time, the lowest electricity consumption 60 Watts, not zero. The mean consumption during the day is 100 Watts and the hourly average oscillates between 80 and 120 Watts. The very low point of demand is 60 % of the mean demand.

The analysis is made for 3,650 refrigerators, and the demand is evened out very finely, in Figure 7 it is not possible to seen the altering consumption of Figure 6. More refrigerators will even the demand even more out. Whereas one refrigerator has a very alternating electricity demand, more refrigerators have a very stable demand, making it possible to predict the amount of consumption in refrigerators for instance in Eastern Denmark.

The size of the electricity consumption in a household refrigerator also inflicts on the usability of refrigerators as DFR. Because installing frequency control device in appliances with small consumptions are expensive compared to the effect on the frequency if one appliance is switched off. Single household refrigerators have a small electricity consumption compared to the need for reserves. Many refrigerators are needed if the effect on the frequency should be measurable. The average refrigerators used in the potential analysis of this report have an electricity consumption of 50 W but new refrigerators can have consumption as low as 22 W (www.elsparefonden.dk..., d. 27-10-2006).

Figure 8 shows the development in the electricity demand of different electricity consuming devices including refrigerators.

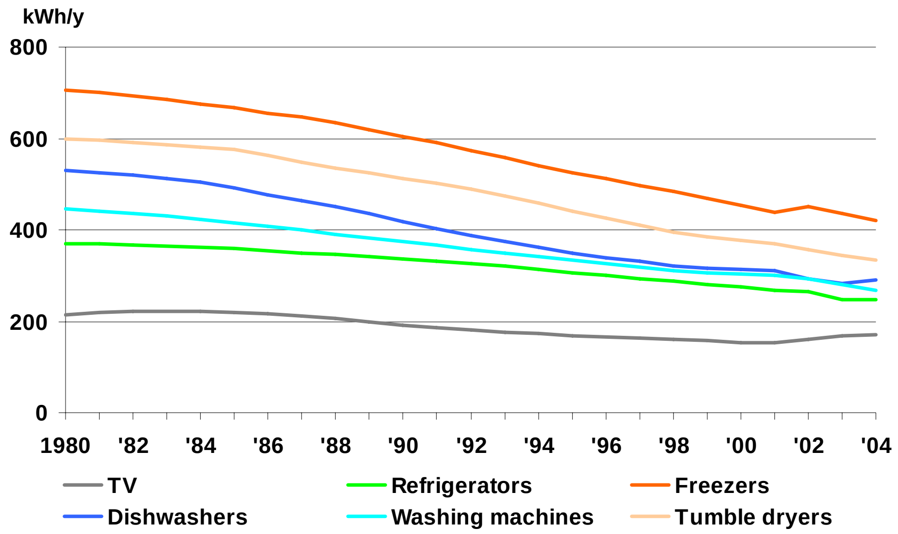

Figure 8 The development in the electricity demand of different electricity consuming devices from 1980 to 2004 in Denmark. (Energistyrelsen, 2005: 32)

As it is seen in Figure 8 the electricity demands of single units of six different technologies in Denmark have been falling since 1980. Resulting in an average consumption of a Danish refrigerator in 2004 equal to 220 kWh/y. In comparison an American refrigerator in 2004 used about 500 kWh/y. (Baker & Sanna, 2006: 6) The demand in American refrigerators is more than twice the demand of a Danish refrigerator, even though also American refrigerators have lower their demand in the past 30 years. The influence on the frequency will be bigger in America than in Denmark if one refrigerator is switched off.

The prices of electronics needed to make a refrigerator usable for frequency control is independent of the size of the refrigerator. This makes it more profitable to install frequency control in American refrigerators. Sizes of demand to the same technology differ from country to country, making different technologies more interesting as frequency controlled reserve in different countries. This makes it important to investigate the different consumptions in a country before installing frequency control devices in appliances.

6.4 Time constant

The time constant is a mathematical expression used in connection with exponential functions. In a cooling or heating process the temperature will change exponentially, because the rate of heat transferred in the process is proportional to the temperature difference between the cooled or heated and surroundings. This difference will fall as the unit is cooled ore heated. In a refrigerator with the compressor turned off the temperature inside the refrigerator will change exponentially as the inner temperature will get closer to the room temperature in the kitchen.

If something hot is cooled by the surrounding temperature, the same exponential behaviour is seen. Figure 9 illustrates the mathematical time constant, for a cooling process.

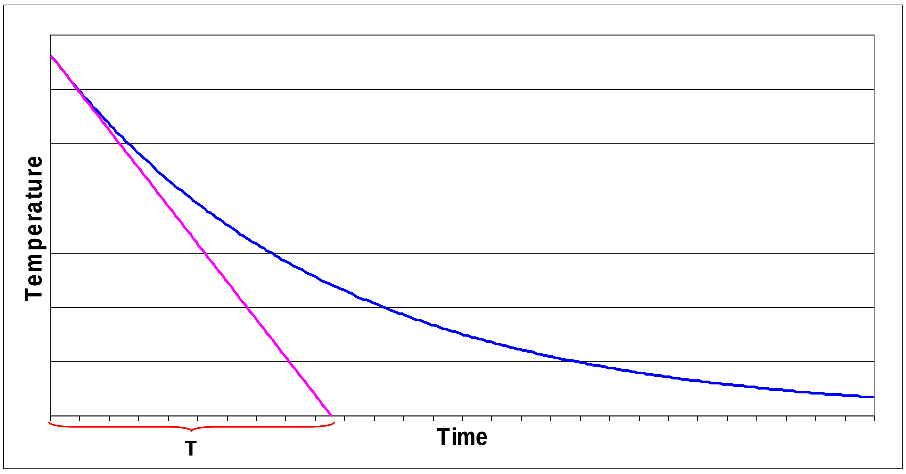

Figure 9 The mathematical time constant.

The time constant is calculated from the slope of the temperature curve in the starting point and the difference between the starting temperature and the surrounding temperature. In the cooling and heating the time constant is a measure for how long it takes for the temperature to fall 36 %, of the starting temperature.

In this analysis the time constant is calculated for a refrigerator from the yearly electricity demand. This simulates normal use of the refrigerator, ensuring that the calculated time constant will represent a normal day where the refrigerator is open and closed and not a made scenario where the refrigerator is closed the whole time. The food contents in the refrigerator will influence the time constant, the more food in the refrigerator the higher time constant, since the food have a higher heat capacity than air. In these calculations the refrigerator is set to contain 10 kg of food, equalling 3-5 liters of milk, juice or yogurt, 2 kg of cheese, butter and sliced meet, 2 kg of fruits and vegetables and 1 kg of meet. The heat capacity of the food is set to the same as for water since most foods contain mostly water. In these calculations the time constant for a new refrigerator is 16 hours, and for an old one: 8 hours. These high time constants indicate that cutting of the electricity to a refrigerator for 15 minutes will not damage the food inside.

But room temperature is not desirable in refrigerators, since most foods will spoil at room temperature. To ensure the quality of the food a limit temperature is set. This temperature level result in a comfort time constant, telling how long a refrigerator can keep the food edible with no electricity.

The National Food Agency of Denmark gives some guidelines for food storage. The general guideline is that the temperature of a refrigerator should not be more than 5 ^{o}C. If the temperature in a refrigerator is more than this, it must not be for more than 3 hours.

As an example the National Food Agency explains that the bacteria Salmonella can grow at 8 ^{o}C but not at 5 ^{o}C. There for the temperature limit in this analyse is set at 8 ^{o}C. (http://www.altomkost.dk/madtilmange/Tilberedning_og_servering/Hygiejne/Opvarmning_og_koeling/forside.htm, 04-10-2006)

The temperature curves of a new and an old refrigerator is seen in Figure 10. The calculations are made in a situation where the compressor is turned of at a refrigerator temperature of 5 °C.

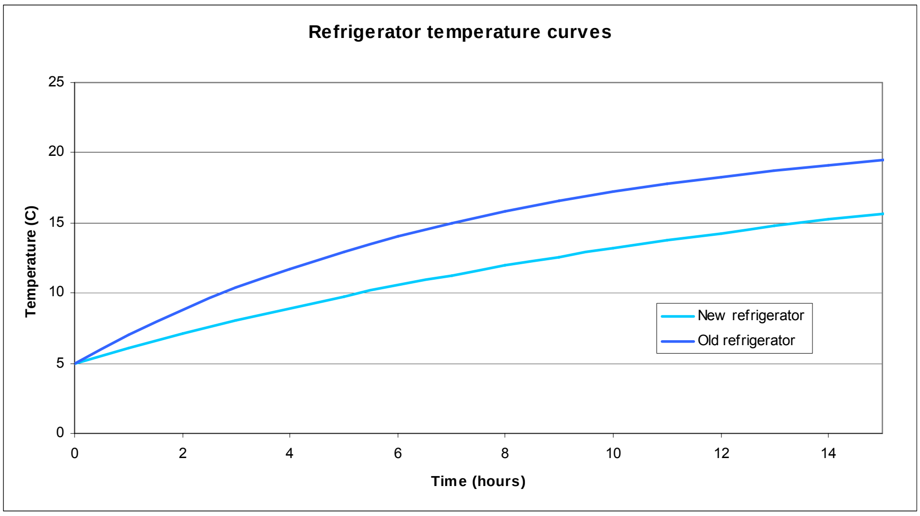

Figure 10 Temperatures of a new and an old refrigerator as a function of time.

As seen in Figure 10 it will take a new refrigerator 3 hours before it reaches 8 °C and it takes an old refrigerator 1.5 hours. Household refrigerators can be turned off for 15 minutes without damaging the food or bothering the consumers. The guideline of 3 hours will never be violated if the refrigerator is cut off for 15 minutes. The temperature in a new refrigerator after 15 minutes will be 5.3 °C, this temperature will not damage the food.

6.5 Requirements of the electronic equipment

In a refrigerator the requirements for the electronics for the frequency control of refrigerators are explained in the following.

There will of cause be a need for a frequency measuring unit. Since the temperature of the refrigerator cannot be too high it would be an advantage to shot off the coldest refrigerators first. This gives the need for a temperature measuring unit.

To control the shot downs by the frequency control, and to make the two measuring units work together, a programmable unit is needed. This unit should measure the temperature in the refrigerator and the frequency in the electricity system. The unit should be program in a way so it only allows the compressor to turn of if the temperature in the refrigerator is below a predetermined temperature. The operations of such system are illustrated in Figure 11.

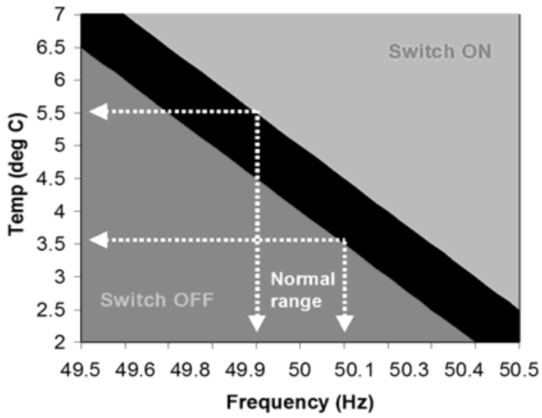

Figure 11 Illustration of the operation of a dynamic demand thermostat. The temperature in a refrigerator vs. the frequency, in the black area the refrigerator should do nothing. (Short, 2006)

In the light gray area of Figure 11 the refrigerator should switch on and in the darker gray area of the graph the refrigerator should turn off. In the black area of the graph the refrigerator should not change its current operations.

Operations without frequency control of the refrigerator would keep the temperature within the temperature range from 4 to 5 ^{o}C. With frequency control the temperature is kept with the range from 3.5 to 5.5 ^{o}C. The expanded temperature range will not damage the food.

6.6 Summary

The potential and the usage are positive features for the use of refrigerators as DFR. Also the possibility to turn a household refrigerator off immediately makes it interesting to use refrigerators as frequency controlled reserve. The comfort time constant is also in a range ensuring the comfort of the consumer.

If refrigerators are to be used as frequency controlled reserve there is a need for installation of new electronic measuring and programmable equipment.

Refrigerators will be damaged if they are turn on shortly after they have been turned off, do to the need of pressure equalization. This demand installation of extra features in the electronics needed for the frequency control. The extra feature can be a time delay making sure the refrigerator will not be turn on before the pressure equalisation is finished, or it can be a valve making the pressure equalisation instantaneously.

7 Freezers

7.1 The technical description

Freezers share the same technology as refrigerator and a thorough description of the refrigeration cycle can be fond in chapter 6 “Refrigerators”. The electricity consuming unit in a freezer is, as in a refrigerator, a compressor. It is the same type of compressors used in the two cooling appliances, but the refrigerant can be different.

In fridge freezers there is normally only one compressor so the same compressor and refrigerant can be used for the required cooling at the different temperatures. Since refrigerators and freezers share the same technology freezers have the same advantages and problems as refrigerators when used as frequency controlled reserve.

The potential in separate freezers are big in East Denmark. Freezers is controlled by a thermostat and connected to the electricity grid all the time. The usage of freezers is perfect for DFR.

7.2 Time constant

The time constant for an old and a new chest freezers has been calculated. For an old freezer the time constant is 17 hours and for a new freezer it is 36. In the calculations the freezer is set to be half full. For freezers the time constant is a bit misleading since the temperature curves of the freezer will be exponential till they the 0 ^{o}C. At this temperature the contents of the freezer will start defrosting and the temperature will not change until the defrosting is over. After the defrosting the temperature curves will be exponential again.

Defrosting is not wanted in a freezer and also temperatures close to the melting point, can damage the food contents. The temperature in a freezer must at the highest be -15 ^{o}C. The comfort time constant is found from the temperature curves of the refrigerator.

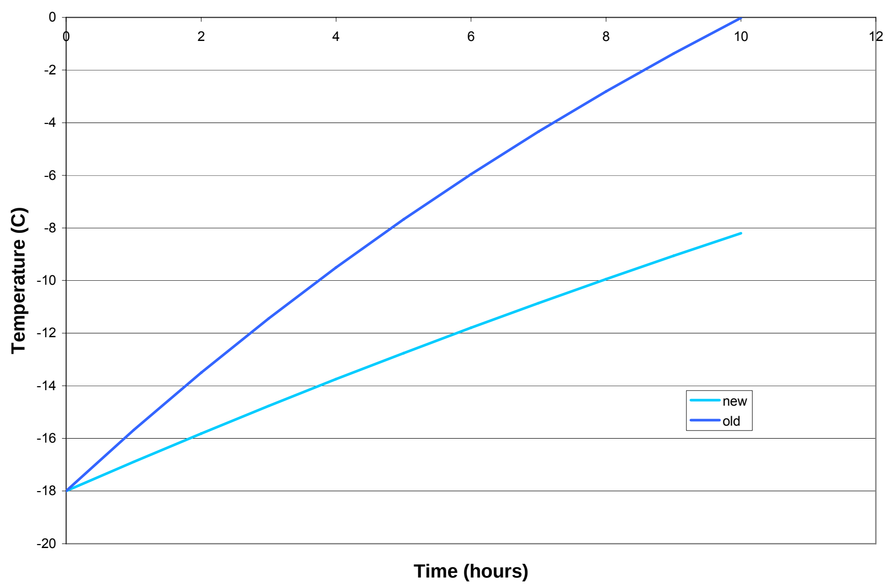

Figure 12 The temperature curves of an old and a new chest freezer.

The comfort time constant of an old freezer is 1.5 hours and for a new freezer it is 2.5 hours. The maximum disconnection period of 15 minutes will not harm the contents of a freezer.

7.3 Requirements of the electronics equipment

A frequency measuring device is needed and to ensure the pressure equalisation a time delay unit. It would be an advantage to make the frequency measurement and the temperature of the freezer work together. As in refrigerators the frequency control device need to make pressure equalisation possible before the freezer is reconnected.

7.4 Summary

The potential and usage of freezer suit DFR very nicely.

Freezers have reconnection problems after a disconnection and some additional features of the electronic equipment are needed in addition to the frequency measuring unit.

8 Air conditioners

Air conditioners are not used much in households in Denmark, there are no estimates of the potential, but many other countries have big consumptions and big potentials for DFR in air conditioners.

In the American study with the ten households, mentioned chapter 6 “Refrigerators”, the average daily electricity demand for air conditioning is 13.6 kWh/day per household. In comparison a Danish fridge freezer consume 1.2 kWh/day. The consumption for air conditioning in one of these American households is the same as the consumption in 11 new Danish refrigerators. The cost of installing frequency control in one American air conditioner will be the same as installing it in a Danish fridge freezer, making it more economically attractive to install frequency control in the air conditioner.

Also in other parts of the world there are many air conditioners and a big consumption in these. Making frequency control possible for air conditioners gives a lot of potential for DFR.

8.1 Technical description

Air conditioners basically use the same refrigerant cycle technology as a refrigerator, a more thorough description can be found in section 6.3 “The use as DFR”.

Air conditioners cool the air of the rooms they are installed in. They are controlled by a thermostat measuring the room temperature. The wanted temperature is set by the consumer.

8.2 The use as DFR

The following section is based on a telephone interview with Mogens Grube from Christian Berg, a Danish seller of cooling systems including air conditioners.

Household air conditioners can be turned off immediately without damaging the equipment. As refrigerators air conditioners have a downtime after a disconnection as the compressors in the refrigerators, to ensure the pressure equalisation.

A thermostat controls the operations of the compressor. The preset room temperature is the controlling parameter.

An air conditioner will be worn out if it is disconnected too many times, since the lubricant will not be distributed optimally if the compressor is interrupted.

Air conditioners contain electronic equipment the frequency control device can be build into this. At this point of time electronic control in air conditioners sets the limit that the air conditioner can only be switched on six times per hour.

With a frequency measuring unit it is possible to use present air conditioners as DFR.

8.3 Summary

Outside Denmark there is a big potential for DFR in air conditioners.

As the freezers and refrigerators air conditioners have some start problems after a disconnection due to the pressure equalisation.

Air conditioners already contain electronic equipment making the installation of frequency control device easier.

8.4 Industrial cooling

Big industrial cooling plants for food storage and space cooling have big electricity demands. They plants share the same technologies as household refrigerators and air conditioners and could be possible for DFR.

Apart from a compressor bigger commercial air conditioning system and cold stores contain pumps, more thermostats and the like. The systems have a shutdown routine of about five minutes before they can be switched off, to make sure the system will not wear out from the shutdown. Therefore bigger industrial cooling systems are not usable as DFR.

9 Electric heating

Electric heating is used both space heating and water heating. The apparatus for the different heating purposes have different forms but the fundamental technology is the same. Electricity is sent through electric heating elements causing them to heat up. The heated elements are cooled by the surroundings that thereby are heated.

For the different heating purposes the surroundings changes. In water heaters the surroundings is the water, the space heating the surroundings is the air in the room and in floor heating the floor construction is the surroundings of the heating elements and the floor transfers the heat to the room above the floor.

In this report electric water heating and electric floor heated are analysed, but since the basic technology is the same the same results are predicted in the other electric heating technologies.

As it was seen in section 5.2 “Potential”, there is a big demand in electric heating in Denmark. In 2001 124,700 detached houses in Denmark had electric heating for space heating using 6,500 kWh electricity on average for heating.

The distribution of the demand for electric heating is seen in Figure 13.

Figure 13 Distribution of the demand for electric space and water heating in East Denmark in 2001. (Data is from Elkraft System)

The results in Figure 13 are made from measurements in households with and without electric heating. The consumption in the electric heating has been found by subtracting the two demands.

The demand in electric space heating is strongly dependant on the season. In the winter there is a big amount of demand and in the summer there is very little demand.

Regarding the use as frequency controlled in the winter months December to February the demand from electric heating is never under 70 MW and seldom below 80 MW. It is at all times in the months from January to March and October to December possible to disconnect the 25 MW, set as a goal in this project. Even in the summer months there is some demand in the electric space heating, and therefore always a potential for DFR.

Most Danish houses are unheated in the summer months. The demand from May to September most probable comes from electric water heating, hot water is also used in the summer period. Some of the demand can also come from electric floor heating in bathrooms; these systems can be switched on all year and also in the summer.

For electric space heating the potential for DFR has a strong seasonal variation, but in the winter there is a big potential for DFR in electric space heating. In section 5.2 “Potential” the demand of the electric space heating were distributed to all hours of the year, but as seen in Figure 13 there is no consumption of electric space heating in the summer. If the demand of the space heating is distributed to the 8 months it is used the potential in these months are 46 MW.

The consumption in electric water heating is distributed all over the year and the potential for DFR is big at all times.

10 Electric floor heating

Electric floor heating systems are electric heating elements embedded in the floor construction or put on top of existing floors in connection with rebuilding.

The systems are controlled by a temperature measurement in the room above the floor or in the floor construction. The room temperature is set by the habitants.

10.1 The use as Frequency controlled reserve

This section is based on a telephone interview with Peter Andersen from Devi, as Danish producer of floor heating systems. Devi is a part of the Danfoss group.

Electric floor heating can be turned off immediately. Do to the inertia in the system the electricity can be turned off, for periods of time without any change in comfort. During normal operations an electric floor heating system is turned on and off, after the room or floor temperature. These temperatures are preset by the consumer.

Electric floor heating is turned on as easily as it is turned off. There is no problem in turning on and off quickly after each other.

The present floor heating technology is controlled by a temperature sensor measuring the room temperature. A mechanical switch switches the electricity on and off according to the required temperature. The communication between the thermostat and the switch can be wireless. At this point of time the floor heating systems runs automatically. The inhabitant sets the wanted room temperature and the automation handles the operations of the system.

If the electric floor heating is to be used as a frequency controlled reserve, a frequency measuring unit must be installed by the current thermostat. It should be made so that the frequency measurement can trigger the mechanical switch and turn off the heating elements. The operations of the frequency control could be similar to the operations of frequency control in refrigerators shown in Figure 11.

The mechanical switch will wear from turning on and off, but since the normal operations also require turning on an off, the wear from the frequency control will not be significant. During normal operations in the winter the electricity is switch on and off 3-4 times per hour.

Old floor heating systems are all mechanical, but newer systems contain a lot of electronics and calculation power. The existing electronics contain the calculation power required for frequency control, therefore only the frequency measuring unit is needed to make floor heating ready for DFR.

With the installation of a frequency measuring unit frequency control is possible with the technology status of present floor heating.

(http://www.devi.dk/F14E47DD-D620-44EA-918B-121E949FD115.W5Doc d. 14-08-2006)

10.2 Time constant

The time constant is explained more through in section: 6 “Refrigerators”.

In this example the time constant is calculated in a room with a floor area of 16 m^2. The floor heating cables is placed below 10 cm of concrete and 2 cm of wooden flooring.

When the electricity in the cables is switched off the temperature in the room is only dependant on the temperature of the concrete and wood in the floor construction.

The heat capacity of concrete is 800 J/kg·K the density of concrete is 2400 kg/m^3. (By og Byg, 2003). The heat capacity of the flooring is 2500 J/kg·K and the density of the wood is 520 kg/m^3. (Danvak, 1997)

When new floor heating systems are installed they are designed to deliver 80–150 W/m^2. In the calculations 100 W/m^2 has been used as the heat loss from the floor construction. This is a bit high since floor heating systems probably have been dimensioned after the coldest days, so the normal heat loss will be lower.

The time constant of the floor construction is 5 hours for the electric floor heating. The temperature curve of the floor heating is seen in Figure 14.

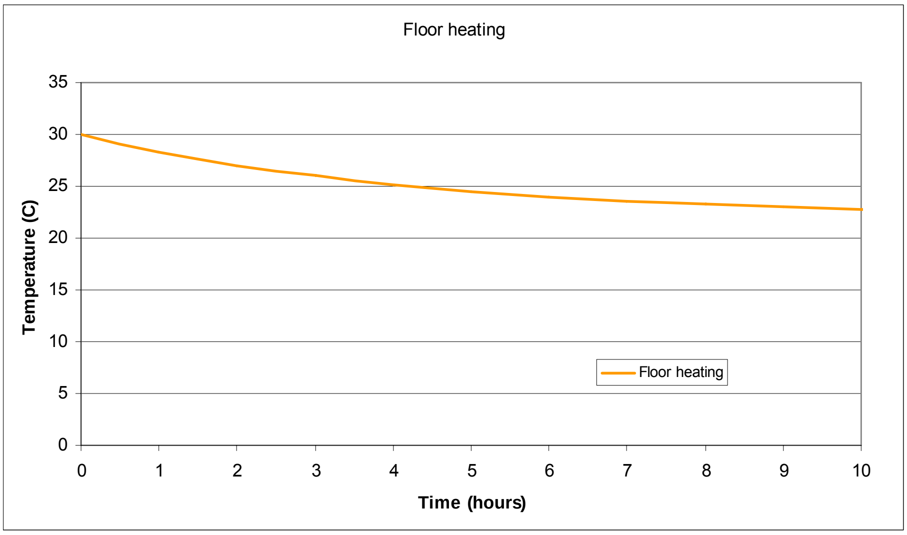

Figure 14 The temperature curve of the concrete in a floor construction.

The time constant of 5 hours indicate that the disconnecting for 15 minutes will not lower the comfort of the consumer. As seen in Figure 14 the temperature of the floor falls from 30 to 25 ^{o}C in four hours. After 15 minutes the temperature is ca. 29.5 ^{o}C and the consumer will not notice of the floor heating is disconnecting for 15 minutes.

The maximal comfort temperature of surface of the floor s 29 ^{o}C and the 30 ^{o}C is set a bit high. The temperature level has some influence in the calculations of the time constant.

10.3 Requirements of the electronic equipment

Frequency control is needed for making DFR possible in electric floor heating systems. No time delay is needed for the electric heating. As a possibility collaboration between the frequency measurement and the room temperature measurement could be made, but this is not a requirement.

10.4 Summary

In the winter period there is a big potential for DFR in electric floor heating. The consumer has very little influence of the variations in the demand for electric heating.

There are no start-stop problems in electric floor heating, but frequency control is required.

11 Electric water heating

The water heated by electricity is mostly used as domestic hot water. The consumption of hot water varies a lot during the day. There will be little consumption during the night, high consumption in the morning and evening and some consumption in the middle of the day.

Hot water is used all year round so there will be little seasonal variation in the demand of the water heaters.

Water heaters are often used in summer cottages this could cause more demand for water heating in the summer and in weekends.

11.1 The use as DFR

The following has been made from a mailing correspondence with Fleming Andersen from Metro Therm, a Danish firm producing electric water heaters.

Electric water heaters can be switched off immediately and if the water heater has been turned off it can be switched back on as quickly as wanted, unless the maximum temperature has been reached.

During normal operations the heating elements in the water heater is switched on and off several times a day. Water heaters are controlled by a thermostat in the water container, switching the heating elements on and off according to the temperature of the water. The consumer sets the wanted temperature in the water heater and has no other influence on the operations of the water heater.

External devices can control the starts and stops of the water heater with other inputs e.g. a timer or other external communications can control the water heater.

No parts of the water heater will be worn more by frequency control than by normal operations.

At this point of time water heaters do not contain electronics. There is no installed calculation power for the frequency control. Water heaters need a frequency measuring device before they can be used as frequency controlled reserve.

11.2 Time constant

The time constant for the water heater is calculated for a water heater containing 160 liters of water. The time constant is calculated from the heat loss from the water heater this means in a situation with no consumption of hot water. This situation is mostly found during the night, where the hot water is not used as frequent.

The time constant for the water heater is 95 hours, this big time constant means that the water heater can be turned off for 15 minutes without the consumer noticing it. The temperature curve of the water heater is seen in Figure 15.

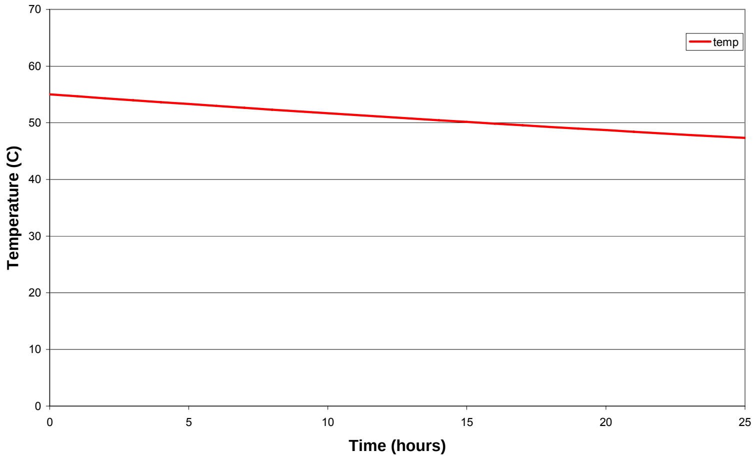

Figure 15 Temperature curve of a water heater with no use of hot water.

The temperature of the water in the water heater is falling very slowly. After 10 hours the temperature has fallen from 55 °C to 52 °C (see Figure 15).

If there is a consumption of hot water, the time constant of the water heater will be lowered. However when hot water is used, new cold water will be added in the bottom of the water heater. The water heater is designed to cerate as little mixing as possible between the hot and the cold water. In the water container stratification will be obtained: hot water will be in the top of the tank, the water getting colder down through the tank. The hot water is tapped from the top of the tank. Even with hot water consumption the water heater can be turned off for 15 minutes, since the hot water in the top of the tank will be used in this period.

A normal shower uses up to 26 litres of hot water. A 160 litre water heater should be able to provide 6 normal showers. The length of a normal shower not specified further and in big families it can be too little and DFR in the water heater will not be a wanted option. But for most water heaters DFR is possible without a loss of comfort for the consumer.

11.3 Requirements of the electronic equipment

A frequency measuring unit is need in the water heater. Collaboration between the frequency measurement and the temperature of the water could be installed but is not necessary.

11.4 Summary

There is a big demand in water heaters in East Denmark and therefore a big potential for DFR. The demand of the water heater is influenced to some degree of the hot water consumption, but the regulation in the water heater is made automatically.

The time constant of water heaters is high and the consumer will not notice if the water heater is disconnected.

Water heaters have no start-stop problems they can be disconnected as often as wanted.

The electronics for the water heaters frequency control is simple and do not need to have contact to the water heater. The contact could be made making sure that the water heaters with the highest temperature are disconnected.

12 Washing machines and tumble dryers

There is a big potential for DFR in washing machines and tumble dryers. The usage of the two appliances very dependant on the consumer and are limited to short periods of a few hours.

This section is based on a telephone interview with Ole Jensen form the Danish part of Electrolux.

All washing machines sold by Electrolux today are equipped with a pause button. This button makes it possible for the consumer to disconnect the washing machines. When the pause button is pressed again the program will start from where the program was interrupted. No parts of the washing machine will ware out or be damaged by the disconnections, and if the interruptions are not too long (days) the clothes in the machine will not be harmed either.

The pause button is now manually controlled by the consumer but if the pause possibility was made automatic it could be controlled by the frequency. At the same time washing machines contain a lot of electronic equipment. Frequency control is not an option in washing machines now, but not much extra electronic equipment is needed. Only the programming for frequency control is needed.

Newer tumble dryers from Electrolux also have the pause button installed and therefore they have the same usability for DFR as washing machines.

Washing machines and tumble dryers can be disconnected instantaneously, they can be disconnected for 15 minutes and they can be reconnected immediately after a disconnection. They already contain electronic control and only programming is needed for DFR to be a possibility.

13 Industrial Cases

Demands in the industrial sector can be bigger than household demands, and the potential for DFR in single units can be bigger than in single household appliances. Therefore the installation of frequency control in industrial appliances can have a relatively lower cost than in household appliances.

In a demand response study of the 25 biggest electricity consumers in the Danish industry it was found that these industries all together could deliver 152 MW of demand response. 3 % of this consumption was available for demand response at all times whereas the rest is available for periods of the year. Not all of this demand is usable for DFR since they cannot be disconnected instantaneously but there will be some potential for DFR in the Danish industry. (Dansk Energi Analyse A/S og Norenergi Aps, 2005.)

Three large power consumers in Denmark have been contacted and are used as cases in this report to make an initial analysis of DFR possibilities in Danish industry.

13.1 Waste Water treatment plant – Lynetten and Damhusåen

The waste water treatment plants, Lynetten and Damhusåen, treat the waste water from 750,000 citizens in Copenhagen and the surrounding areas. The two plants used ca. 44,000 MWh in 2005 equal to an average consumption of 5 MW. It has been investigated if some of this demand can be used as DFR.

This section is based on interviews with Bjarne Andersen, Kim Rindel og Hans Jørgen Olsen from Lynetten.

The plant, Lynetten, is divided in two sections, one section dealing with water treatment and another part dealing with the sludge treatment.

The sludge is parted from the waste water, dried and burnt. The processes in this section is very dependent on each other, if one part process is disconnected a series of other processes are stopped. The environmental requirements to the plant make it impossible to disconnect selected demands in this section. In the sludge treatment there is no potential for DFR.

In the water treatment section some part processes can be disconnected for 15 minutes without damaging the equipment or the output. If processes are to be disconnected it is important to design the disconnection device to ensuring that the process will restart automatically and that the process are not disconnected in periods with overload.

An example of a process with a large power consumption which can be used for DFR is aerating. The aerating process can be turned off instantaneously and can be disconnected for 15 minutes without damaging the process or the equipment. At Lynetten the aerating takes places in 10 tank set, each set consisting of two tanks. In each tank 4 aerators are installed, giving a total of 8 aerators in a tank set. The 4 aerators in one tank are running per tank set during normal operations. The two tanks in a tank set take turns being in operation. During normal operations 40 aerators are running. It will be during normal operations disconnections can be made. In periods with big water loads all 80 aerators are operating at the same time. This overload only happens in short periods, with strong rain in Copenhagen, the aerators should not be disconnected in these periods.

The potential for DFR of disconnecting the aerators are: 10 tanks with 4 aerators per tank and each aerator use 40 kW. The total potential for DFR is 1.6 MW.

This demand is 32,000 times bigger than the demand in a household fridge freezer. The installation price of the frequency control is probably lower for the 10 tank sets of the waste water treatment plant than for 32,000 fridge freezers.

At the plant Damhusåen, there is no sludge treatment, but only water treatment, the sludge is transported to Lynetten after separation from the water and after drying. In the drying process at this plant, 4 large centrifuges separate the sludge from the water.

These 4 centrifuges can be used for DFR. The centrifuges can be disconnected instantaneous without damaging the equipment or the output and they can be disconnected for 15 minutes. The centrifuges run with 3000 rpm in normal operation. If the centrifuges are disconnected from the electricity supply, it will take 5-10 minutes before the centrifuges stand still, if they are not mechanically braked. In this period there will be no electricity consumption in the centrifuges. But to make the centrifuges ready for the next start up, water will be poured into the centrifuges as they slow down. The water comes from another system, which cannot be used for DFR and will be in operations after the centrifuges have been disconnected.

The consumption of a centrifuge and its feed system is 200 kW, the total demand in the 4 centrifuges is 0.8 MW. The centrifuges normally run in the daytime so this reserve is only usable in the daytime.

The waste water treatment plants of Copenhagen are able to supply 2.4 MW in the day time and 1.6 MW at other times. In case of strong rain in Copenhagen and the surrounding areas the plants is not able to disconnect their demands, and there is no potential for DFR in these periods.

If the demands of the waste water treatment plants are to be used for DFR the controls for disconnections have to be installed. The disconnections and reconnection must be automatic and they must not cause extra work for the plant workers.

The waste water treatment plans already have a computer based control system, and the additional frequency control should cooperate with this system.

13.2 UPS – Banedanmark

UPS-units (Uninterruptible Power Supply) are used to ensure the power supply to appliances that must operate at all times also in case of blackouts. These vital demands are connected to the UPS-units which take over the supply when the ordinary supply fails.

UPS-units are design so that the electricity to the demand is going through the UPS before it reaches the demand. If irregularities is detected the UPS supply the demand with electricity for as long as necessary. The units are designed to take over the supply of the demand instantaneously and with no warning. Therefore the units are suitable for DFR. If a UPS is switched on, it will provide electricity for the connected demand relieving the power system of the demand. UPS systems are ready to start operating at all times, making the usage suitable for DFR.

Since using the UPS as DFR relieve the power system of the supply to the demand, the potential for DFR varies according to the demand. UPS-units are designed to have an over capacity so if the potential for DFR is calculated from the nominal effect of the UPS a percentage must be subtracted.

Banedanmark (Rail Net Denmark) is the owner of the railways in Denmark. This section is based on interviews with: Ken D. Larsen, Peder Fischer Nielsen and Niels Helmø, from Banedanmark.

UPS-units contain batteries or small generators for power production. Battery units maintain a stable frequency in island mode, whereas with generators the frequency can oscillate. In this case only UPS-units with batteries are investigated.

Alongside the Danish railways signal lights are installed to control the train traffic. These signal lights need to be in operation at all times to keep the train traffic running. Therefore UPS-units are installed in connection to the signal lights. The purpose of the units is to supply signal lights with electricity, in periods with no ordinary supply, long enough for a service mechanic to get to the sight.

In the Copenhagen area there 80 UPS-units are installed in connection with the railroads. The units have an effect of between 2 and 80 kVA. The capacity of the UPS-units can supply the connected demand in one and a half to two hours. Switching the UPS-units on for 15 minutes in case of under frequency will not cause problems for the train safety, not even if a blackout should occur after the 15 minutes.

Some examples of UPS-units in the Copenhagen area can be seen below:

Table 2 Examples of effect of Banedanmarks UPS- units. (Data from Banedanmark)

Unit number	Nominal effect (kVA)	Real effect (kW)
1	20	14
2	15	11
3	20	14
4	2	1.4
5	80	58
6	8	5.8
Total	145	104

In Table 2 the nominal effect have been converted into a real effect with a conversion factor of 0.8 (APC, 2006), and the potential for DFR is set to 90 of the nominal effect.

As seen in Table 2 the 6 UPS-units of Banedanmark can provide 0.1 MW of DFR. If these 6 UPS-units are said to represent the average of the 80 Copenhagen UPS-units, the total amount of DFR from the Copenhagen UPS-units of Banedanmark is 1.5 MW. This is 30,000 times the amount of DFR from an average fridge freezer. Installing frequency control in the 80 UPS-units will probably be cheaper than installing it in 30,000 refrigerators.

The UPS-units of Banedanmark are already able to measure the frequency in the power system, but programming or change of set points is needed to make DFR an option. Adding the proper programming to present UPS-units of Banedanmark in Copenhagen will provide 1.5 MW of DFR at all times.

If frequency control is installed in all the UPS-units of Banedanmark all over Denmark, not only in Copenhagen, there would be a much bigger potential for DFR.

13.3 Hospital – Rigshospitalet

A hospital has large power consumption, some of the consumption is vital and some can be disconnected as DFR.

This section is based on a telephone interview with Hugo Petersen from Rigshospitalet, the National Hospital of Denmark.

Some demands of the hospital are similar to household demands and some demands are industrial. In Table 3 a number of examples of demand suitable for DFR are shown. The refrigerators and freezers share the same technology as household refrigerators and have the same DFR possibilities as the household appliances. The cooling and ventilation units are small units that can be switched off for instantaneously and can be disconnected for 15 minutes without loss of comfort.

Table 3 Demands suitable for DFR in Rigshospitalet. (Data from Rigshospitalet)

	Number	Consumption per day (kWh/unit)	Total consumption per day (kWh)	DFR potential (kW)
Freezer (-20 °C)	535	0.84	449	19
Freezer (-80 °C)	160	15	2400	100
Refrigerators (5 °C)	1300	0.35	455	19
Cooling (comfort)	30	25	750	31
Ventilation 1	300	50	15000	630
Ventilation 2	50	110	5500	230
Total	2375		24554	1030

As shown in Table 3 the demands in Rigshospitalet can provide about 1 MW of DFR in total. But as household refrigerators and freezers, the refrigerators and freezers of the hospital are only using electricity in some periods, when the compressor is turned on. Also the comfort cooling and the ventilation is switched on and off according to the cooling demand and ventilation demand. This means that not all of the demands are available for DFR at all times.

It is estimated that one third of the demand is in operation at all times. This means that the demands in Rigshospitalet can provide minimum 0.33 MW of DFR. But since the frequency control should be installed in all the different appliances of Rigshospitalet the advantage of using DFR in the hospital is not as big as in the waste water treatment plants or the UPS-units.

14 Comparison of the different technologies

This chapter sums up the results of the different technologies use as DFR and the best technologies for DFR are pointed out. In the end of the chapter some examples of how demand can provide 25 MW of reserves are seen. The installation costs of these examples are estimated. More thorough descriptions of the technologies can be found in the chapter of each technology.

The results for the household demands are compared in Table 4, in the table "+" indicate that the technology is positive regarding DFR and "÷" indicate that the technology is negative regarding DFR.

Table 4 Summary of the DFR results for the investigated household technologies.

	Turn off	Instant turn on after stop	Electronic control installed	Potential	Constant electricity demand	Possible now
Refrigerators	+	÷	÷/+	+	+	÷
Freezers	+	÷	÷/+	+	+	÷
Air conditioners	+	÷	÷/+	+	+/÷	÷
Water heaters	+	+	÷	+	+	÷
Floor heating	+	+	÷/+	+	+/÷	÷
Washing machine	+	+	+	+	÷	÷

As seen in Table 4 all the investigated household technologies are able to be disconnected instantaneously without damaging the equipment. The technologies can be disconnected for 15 minutes without loss of comfort.

After disconnections the technologies containing a compressor: refrigerators, freezers and air conditioners, are not able to be reconnected immediately after disconnection. Pressure equalisation is needed before the compressors can reconnect.

Only washing machines always contain electronic control equipment, probably making the installation of frequency control cheaper. Water heaters do not contain electronic equipment. Most new appliances of the other technologies contain electronic equipment.

The potential for DFR in all of the technologies are big. The usage of refrigerators, freezers and water heaters are very suitable for DFR since the consumer influence on the power consumption is little. Air conditioners and floor heating has some seasonal variation, air conditioners is used in the summer and floor heating in the winter. But in the periods where the appliances is used the consumer have little influences on the consumption. Washing machines only consume electricity when it is washing clothes; the consumer has a big influence on the consumption of a washing machine.

In all of the household technologies additional electronic frequency control is needed before DFR is possible.

Water heaters are the appliance most useful for DFR, as seen in Table 4 the only "÷" regards frequency control and all the technologies need installation of frequency control before they can be used as DFR.

Floor heating has many of the same characteristics as water heaters, but is mostly used in the winter period. In the winter floor heating is very useful as DFR and has a very large potential for DFR in this period.

Refrigerators and freezers have large potentials for DFR but they have some technical problems regarding the reconnections. These problems make frequency control for refrigerators and freezers a little more complicated than for electric heating.

The usage of air conditioners and washing machines make these technologies a little less interesting for DFR. However washing machines and tumble dryers only need frequency measurement and programming for making frequency control possible.

The industrial cases are summarised in the following.

In the waste water treatment plant there is a very big potential for DFR equal to 1.6 MW or about 32,000 fridge freezers. But some of the demand is only active in the day time and some cannot be switched of in periods with strong rain. Since there is periods where demand cannot be disconnected some of the household technologies have a better usage for DFR. But I probably will be cheaper to install frequency control at the water treatment plants than in 32,000 fridge freezers.

The UPS-units of Banedanmark have usage, potential and technical possibility of DFR. Frequency measuring devices are already installed in the units and with additional control programming DFR is an option for UPS at this point of time. It is possible that setting a new set point for the frequency will make DFR possible in the UPS-units without additional programming. The potential for DFR in the Copenhagen UPS-units of Banedanmark is 1.5 MW or 30,000 times bigger than for an average fridge freezer. The price for frequency control will be low for UPS-units, since the measuring unit is already installed only programming or change of set point is needed.

At the hospital a large number of small demands are able to provide DFR. The potential for DFR is 1 MW. The appliances for DFR in the hospital are similar to household appliances and the number of appliances is big. The advantage of installing fewer frequency control devices for big industrial demands than for household demands is not present in the hospital case. There could be some advantage in having the same administration for all of the demands in regards to the payment possibilities. It would only be necessary to make one contract for all of the demands and not one for each household.

14.1 25 MW reserves provided by demand

Some examples of how the demand in East Denmark can provide 25 MW reserves for the power system are seen below.

Table 5 Examples of how the demand can provide 25 MW of reserve.

	EX 1		EX 2		EX 3		EX 4	
	%	MW	%	MW	%	MW	%	MW
Water heaters			10	3.1	10	3,1	33	15,2
Space heating	10	4.6	10	4.6			33	10,2
Refrigerators	20	11.8	15	8.9	25	14,8		
Freezers	20	6.3	10	3.2	25	7,9		
Washing machine			3	0.7				
Tumble dryer			3	0.5				
Water treatment		1		1,6				
UPS		1,5		1,5				
Hospital				1				
Total		25.2		25.1		25.8		25,4

Example 1 in Table 5 shows how 10 % of electric heating, 20 % of refrigerators and freezers, 1.5 MW of UPS and 1 MW at the waste water treatment plant can cover the 25 MW of reserve. This example could represent a winter night.

Example 2 shows how little percentages of all the technologies can deliver the 25 MW of reserve. This example requires that 3 % of washing machines and tumble dryers are in operation and that it is in winter time to make sure the electric space heating is in operation.

Example 3 shows how 25 % of refrigerators and freezers and 10 % of water heaters can provide the wanted 25 MW. This example should be possible at all times during the year.

Example 4 is in the winter, in winter electric floor heating and water heating can cover the 25 MW. Floor heating has a potential of 46 MW and water heaters have 31 MW. If a third of both of the demands are disconnected the amount of DFR of these two technologies are 25.4 MW. Since both technologies have start-stop operation, all of the appliances should be available for DFR to ensure that enough of the appliances are switched on to fulfil the 25 MW. If not all appliances are available it is better to divide the reserves on more technologies.

Example 1 and 3 are the most realistic, but as seen many different combinations of demand technologies can provide 25 MW of reserve.

If the price of a frequency control device is estimated to be 200 DKK in an appliance that already have electronic control installed. For appliances without electronic control the prices is estimated to be 300 DKK. Based on these estimates the installation prices of the four examples can be calculated, the results are seen below. In the calculation refrigerators, freezers and water heaters are set to contain no electronic control. The price of frequency control for the industrial demands is set to be the same as for household technologies. This probably is a bit low, since overall control for the DFR in the industry can be needed.

Table 6 Estimated prices for the 25 MW of DFR in the four examples.

	Number of appliances	Installation cost (mill DKK)	Price of reserves (mill DKK/year)
EX 1	1,110,000	327	41
EX 2	879,000	248	31
EX 3	1,353,000	406	51
EX 4	305,000	71	9

As seen in Table 6 example 4 is by far the cheapest example, this example only contain DFR from electric space and water heating. The demands of the two technologies are big and few appliances are needed for the DFR, but the example still demands that all electric space and water heating is used for DFR.

The price of traditional reserves is between 200,000 and 500,000 DKK/MW/year. The price of 25 MW is between 5 and 12 mill DKK/year. In the calculation of the yearly price of reserves for the demand a rate of 5 % and the appliances used for DFR are set to last for 10 years. As seen in Table 6 example 4 is in the middle of the price range for traditional reserves. It is possible to make DFR for the same price as traditional reserves.

15 Frequency control devices

15.1 Tell-it-Online – Electronic Housekeeper

Tell-it-Online is a Danish company providing telemetric systems to both private and industrial clients. In the beginning of 2007 they release a new system for households; the system is called Electronic Housekeeper. This section is based on mailing correspondence with Niels Lisberg and Frans Merrild from Tell-it-Online.

This system consists of a central controlling unit and a number of satellite units sending and receiving information to and from the central unit. The satellite units are connected to selected appliances in the household. The Electronic Housekeeper is installed in private households making the home "Intelligent".

The system is connected to the internet with the same technology as the wireless connections in laptops. It also communicates between the units with this technology. The system combines news, entertainment, communications, surveillance and water, heat, and electricity consumption in the household. The system streams news from the internet, can play music, displays mailing programs and the calendar of the consumer and the system can be used as burglar alarm. The central unit of the system is equipped with USB inputs making it possible to transfer data to and from the Electronic Housekeeper to other computers.

The interesting part of the system in this project is the energy function. This function gives possibilities of controlling and monitoring the consumptions of water, heat and electricity in the household. The system also monitors consumer statistics letting the consumer no what the consumption in the household is and if it changes. Especially the electricity part of the system is interesting in this project.

In the system it is possible to time the electricity demand in for instance in the lighting switching the light on and off after a pattern decided by the consumer. The consumer chooses the appliances they want to connect to the system and set the timing and other set point of the system.

When the system is bought the electricity function in the system can disconnect demands if the load in the household are about to reach a level that will blow the fuses. For this option there is a function in the Electronic Housekeeper where demand can be categorised after their importance.

The Electronic Housekeeper contains equipment for current measurements and for frequency measurements. Frequency control can be made by the Electronic Housekeeper with a software upgrade; the consumer can download from the internet. It is not standard in the system but it is a possibility, the programming already exists. Today it is technically possible to make frequency controlled demand by using the Electronic Housekeeper, and in a short time it will be commercially accessible in the Danish market.

The price of a system consisting of a central unit and two satellite units is about 4,000 DKK, this is not a high prices considering the fact that it is not only the frequency control possibility. The system is too advanced to the frequency control alone; it would properly be possible to make systems only for frequency control cheaper than the 4,000 DKK.

Different satellite units can be needed for control of different consuming appliances. They can be bought separately and installed in the existing system during the use of the system. The price of the satellite units are approximately 400 DKK.

16 Conclusion

It is technically possible to replace a part of the reserves in the central power plant by disconnection selected demands. Both in households and in the industry it is possible disconnect various demands without damaging the equipment or bothering the consumer.

In households the most useful demands for the DFR are:

Electric water heaters have a large potential for DFR, the consumption is distributed all over the year and they have no start-stop problems. Technically water heaters are usefull for DFR if frequency control devices are installed.

Electric floor heating has large potential for DFR in the winter and, the usage in the winter and the technical options are positive for DFR in electric floor heating. Frequency control devices are needed to make DFR possible in electric floor heating.

Refrigerators and freezers have an enormous potential for DFR, their usage is also very useful for DFR. But refrigerators and freezers have some start-stop problems and therefore the frequency control for this type of demand needed some extra features.

Air conditioners have a large potential for DFR outside Denmark mostly in the summer period. Air conditioners have the same start-stop problems as refrigerators and the same type of frequency control device is needed.

Washing machines and tumble dryers also have potential and the technical possibility for DFR, but the alternating usage makes them less useful for DFR than the other technologies.

The technology to make the frequency control possible in households exists at this point of time and will be launched in the Danish market in the beginning of 2007 by the telemetric company Tell-it-Online.

In the Danish industry three examples have shown that some demands can be disconnected and used for DFR. The demands in the industry are bigger than household appliances and have a big potential for DFR. But the timing and usage of the demand are makes the industry a little less favourable for DFR than some of the household demands.

The 25 MW's of reserve this report aimed for can be provided from the household demand and from the industry, there is a lot more potential and more than the 25 MW can be covered by the demand.

An example of how to provide the 25 MW could be: 25 % of the household refrigerators and freezers and 10 % of the water heaters.

It is possible to make DFR for the same price as for traditional reserves; the best example the price is 9 mill. DKK/year for 25 MW of reserve.

It would be interesting to investigate more demands both in households and in the industry and in commerce and service, e.g. electric ovens, pumps, kitchen equipment, lighting, other types of electric heating and ventilation.

Many other parts of using the demand for DFR should be investigated further e.g. the payment of consumers, requirements of the electronic frequency control devices, the administration of demand as reserve and the effect on the frequency in the power system need to be modelled and simulated.

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Ørsted•DTU
Center for Elteknologi (CET)
Danmarks Tekniske Universitet
Elektrovej
Bygning 325
2800 Kgs. Lyngby
Denmark

www.oersted.dtu.dk/cet
Tel: (+45) 45 25 35 00
Fax: (+45) 45 88 61 11
E-mail: cet@oersted.dtu.dk