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Demand as Frequency Controlled Reserve

*Final report of the PSO project*

Research Project, September 2008
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This report summarizes the research outcomes of the project ‘Demand as Frequency Controlled Reserve (DFR)’, which has received the support from Energinet.dk’s PSO program, Grant no. 2005-2-6380.

The objective of this project is to investigate the technology of using electricity demands for providing frequency reserve to power systems. The project consists of five work packages, including

- Background and perspective
- Dynamical simulation of chosen concepts
- Monitoring demand as frequency controlled reserve
- Strategy and practical implementation
- Conclusion and evaluation

Within the project, the frequency quality of power systems has been evaluated, the potential and economy of DFR compatible loads in Denmark has been investigated, control logic has been designed, power system impact has been investigated, potential monitoring method and business models have been evaluated and an implementation strategy has been suggested.

The tasks and goals of the project have been successfully accomplished based on which the conclusion and future recommendation have been made.
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Last but not least, the team would give thanks to all those who have given their valuable supports in one way or another.
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1 BACKGROUND AND PERSPECTIVE

In the electricity system, there is a need for reserve to re-establish the power balance after contingencies. At this point of time, reserves are primarily delivered by central power plants. Electricity demand can be disconnected much faster than generation can be increased, when the frequency drops in the electricity system, and can be used as reserve. For some types of demand, a short - 1 to 15 minutes - disconnection does not influence the function of the equipment or the comfort for consumer. Electric heating, refrigerators and freezers are examples of demands that can be used for frequency controlled reserve.

In Denmark East, which is part of the Nordel interconnected system, 100 MW frequency controlled reserve must be available and must be activated within 30 sec. A part of this can be realised by demand.

Analyses of frequency data have shown that there are hundreds of events per month with frequencies below 49.9 Hz. However the duration of the under frequencies is often very limited – typical 30 sec. It is also shown that the majority of the under frequency events are not related to disturbances, but to intra-hour imbalances related to the market design with hourly prices. The probability of under frequencies has increased during the last 10 years.

Household appliances like a large number of refrigerators and freezers can provide a stable and predictable reserve, but the cost (€/MW) of controlling a large number of units can be high. Electric heating varies according to outdoor temperature but can be predicted with reasonable accuracy and may be a more attractive candidate for demand used as frequency controlled reserve. Also, industrial demand can be used and further investigation into the cost of the control equipment must be done to fully explore the potential of demand as reserve.
1.1 Background

The electricity system must continuously be balanced to maintain a secure operation. Today, mainly generation is used to achieve the balance, while electricity demand has a passive role.

It is well known that demand can compete with generation in the form of demand response, where demand e.g. is adjusted according to electricity prices in the day ahead-market (Nordel, 2004). In some situations high prices exist as price peaks for short periods, e.g. 1-3- hours. Demand can react to these price peaks by delaying the consumption for a few hours. In a dry year, prices can be high for months (as in the wither 2002/3 in the Nordic system). In such situations, energy intensive industry can reduce production and buy materials on other markets.

However, demand can also be used for reserve. Different types of reserve are vital to the stability of the electricity system. Some reserve must be activated within 15 minutes and must be active for an hour or more. Other reserve must be activated almost instantaneously with 50% within 5 sec and 100% within 30 sec. This type of reserve is called frequency controlled disturbance reserve in Nordel.

To use demand as reserve can take many forms. Today, disconnection of demand i.e. load shedding is considered the last resource and whole areas are shed if the frequency drops below 49 Hz. The shedding of whole area will undoubtedly impact all customers and potentially disconnect the embedded Distributed Generations (DGs) that can contribute to frequency control. Instead US based Pacific Northwest National Laboratory (PNNL, 2003, Smith and Kintner-Meyer, 2003) has suggested that individual household appliances suitable for temporary disconnection can be used for reserve, e.g. refrigerators and air condition. Similar suggestions have been made in UK by Short and Leach (2006) and Hirst (2006). The idea was presented as early as 1979 (Schweppe, 1979). The availability of low cost micro electronics makes these ideas attractive.

Already today the frequency influences the electricity demand, since the aggregated electricity demand is slightly dependent of the frequency. E.g. a motor used for lifting material would have a linear relation between frequency and electricity demand (1% reduction in frequency would decrease the demand with 1%). A motor running a ventilation system would react as the third power of the frequency (1% reduction in frequency would decrease the demand with 3%). Since many other electricity demands, as electric heating or lighting, have a diminishing relation to frequency it is estimated by Nordel (2004, b) that the self regulation of the demand is in the order of 200 MW when the frequency decreased from 50.0 to 49.5 Hz (1% reduction in frequency decrease the demand with 0.4%, assuming a total demand of 50,000 MW). Frequency drops already
decrease the demand and by deliberate disconnection of non-essential demand the frequency response of demand can be enhanced. Well-designed this can increase the stability of the electricity system.

Electricity demand can be attractive for frequency controlled reserve because of the quick response. In many cases disconnection of demand can deliver 100% impact within a second. The maximum period of disconnection of 15 minutes can be delivered by many types of demand without loss of comfort, e.g. electric heating. The consumers would often not notice a short disconnection of the heating.

To use demand as reserve is well known in some countries. In Finland industrial 1,000 MW demand from wood processing, chemical, and metal industries are used as frequency controlled as well as manual reserve (Fingrid, 2005).

1.2 Nordel and Denmark East

Nordel has decided that the frequency controlled disturbance reserve must be 1,000 MW, and must be activated linearly between 49.9 and 49.5 Hz. This reserve is distributed to the different Nordel areas according to the size of the local dimensioning fault, e.g. Eastern Denmark must have 100 MW. These reserves are typically delivered with 50 MW by the HVDC connection, Kontek, between Eastern Denmark and Germany, and 50 MW from central CHP plants that can increase power generation by reducing the heat production. Both these reserve are activated at 49.5 Hz. 50 MW are reserved for this purpose in both direction of the Kontek connection. Also, valving is used at selected power plants, this can be activated linearly between 49.9 and 49.5 Hz.

The cost of the 50 MW reservation on the Kontek cable can be estimated based on the day-ahead prices in Eastern Denmark and Germany. With data from 2001 to 2005 the average annual value can be calculated to 95,000 €/MW per year.

The Nordic electricity system needs new resources to maintain a high quality of the system frequency. Analyses show that in 2005 and 2006 the frequency was below 49.9 Hz in more than 0.3% of the time. In 0.8% of time the frequency was over or under the normal interval (49.9-50.1 Hz). This is more than a factor 3 higher than the goal Nordel has expressed (Bakken and Petterteig, 2005). When the system frequency is below 49.9 Hz, many of the reserve are already used and the system stands weakened against serious faults, like an outage of a transmission line or a power plant.

Figure 1 illustrates the decreased frequency quality in the recent years. While the probability of over and under frequencies peaked in 2003, the probability is still much higher than in the period 1995-98. The liberalisation and the design of the electricity
market are considered to be the main reason for this tendency. E.g. in the spot market prices (and with prices also the dispatching of power plants) are established per hour and as a consequence often intra hour imbalances exist.

The increase in the probability of over frequencies is even stronger, but this is not considered to be a major problem. All reserves are intact in situations with over frequencies, so the system stands strong against contingencies.

![Figure 1. Probability of frequencies over and under the normal interval (49.9-50.1 Hz). Data from August 1995 to August 2006. 1 minute values.](image)

The importance of market design can also be seen in figure 2, where the probability of under frequency has been mapped against the minute in the hour. The probability is much higher in the first 15 minutes of the hour compared to the rest of the hour. The probability of under frequencies is higher when the load is low, as in summer and in the night. The inertia of the system is reduces is these cases, leading to wider frequency discursions.

A logistic regression has been performed on 10 sec. data covering the period August 2005 to December 2005. The time of day has been described with 6 dummy variables, the minutes in the hour with 6 dummy variables, and the month is considered a linear variable (8 to 12). With this model the probability of under frequency was found to be 2% in summer nights compared to 0.1% in winter days.

Many under frequency events (just below 49.9 Hz) are not caused by contingencies, but simply by intra hour imbalances related to the dispatching of power plants. While more
than 10,000 events per month occur (see table 1), only a small fraction (<1%) of these are related to technical faults, such as generation outages.

![Probability of frequencies under 49.9 Hz within the minute of the hour. Data from Phasor Measurement Units (PMU’s), April 2005 to March 2006. 0.02 sec. values.](image)

The periods with under frequency (<49.90 Hz) are often very short, 0.8 sec. in average. In less than 5% of the cases the duration is more than 1 second. Many types of demand can deliver the service of disconnecting is such short periods. Figure 3 and Table 1 show statistics for different under frequencies.
Figure 3 analyses the durations of low frequency events, where the x-axis is the duration of low frequency event, and the y-axis is the probability of frequency below certain level with duration not less than the corresponding value at the x-axis. For example, the probability of frequency lower than 49.9 Hz and with a duration of 10 sec. or longer is approximately 0.003. It is observed as the duration increases, the probability of system frequency below certain limit reduces. If we implement a DFR appliance to be disconnected and reconnected back to the grid at the same set point, Figure 3 actually shows the operation statistics of the appliance, i.e. how often and long it will be disconnected. For example, if we choose 49.9 Hz as the set point, the probability of the
DFR appliance to be disconnected with a duration not less than 10 seconds is approximately 0.3% of the time.

The Nordel is a relatively small system (70 GW peak), while the UCTE is larger (350 GW) and the Western American system (WECC) is in between (150 GW). The frequency quality is much better in the UCTE system than in the Nordel system. The probability of a frequency below 49.9 Hz was only 0.008% – a factor 50 less than in the Nordel (UCTE data is 5 sec values for 2005). However, the tendency of higher probability in the beginning of the hour is also clear in the UCTE system. Data from WECC indicate the same tendency.

1.3 Demand as reserve

Several types of electricity demand are not-essential in the meaning that the demand can be disconnected in short periods without disturbing comfort or the involved process. Several of the demands that can be used as frequency controlled reserve act as a kind of energy storage. Electric heating for space heating or for hot water have the thermal storage of the heated air or water. A few minutes of disconnected electricity will reduce the temperature, but not to a degree the consumer will notice. Often electric heating is controlled by an on/off relay which operates with similar temperature variations. Refrigerators and freezers have energy storage in form of the cold content of the appliances, and some industrial electricity demands have storage in the form of a physical storage for the products produced. The temperature of the refrigerator or freezer will not be raised drastically by a 15 minute disconnection.

A survey of the best demand to be used for frequency controlled reserve has been performed based on data from Denmark. The results are summarised in table 2.
Some of the appliances have constant electricity consumption during all hours of the year. This is the cases when a large number of units of refrigerators, freezers or water heaters are considered. The variation due to user interaction is limited and the seasonal variation is little.

Other electricity demands, like electric heating, have significant seasonal variation. However, the consumption can be predicted based on the degree days. If the electric heating from few houses are aggregated it is easy to predict. Based on a data set with hourly electricity demand for electric heating in 22 households it is possible to construct a very simple model with two variables (degree days and degree days at night) with a $R^2$ of 86.2%. Data from the EFFLOCOM project (Kofod and Togeby, 2004) and covers the period from November 2003 to March 2005. In this analysis the periods with price driven interruptions of the electric heating is omitted. With e.g. 1,000 houses an even higher degree of predictability can be expected.

For appliances like washing machines and tumble driers the daily variation is high, typically with no demand at night.

With electric heating disconnection and reconnection can happen without delay due to the appliance and no restriction regarding the time between disconnection and

<table>
<thead>
<tr>
<th></th>
<th>Possible to disconnect within 1 sec. of a under frequency</th>
<th>Possible to reconnect instantly after frequency has recovered</th>
<th>Electronic control installed</th>
<th>Constant electricity demand</th>
<th>Potential MW average (East Denmark)</th>
</tr>
</thead>
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<tr>
<td>Refrigerators</td>
<td>+</td>
<td>+</td>
<td>+/-</td>
<td>+</td>
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</tr>
<tr>
<td>Freezers</td>
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<td>+/-</td>
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<tr>
<td>Air conditioners</td>
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<td>+</td>
<td>+/-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
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<td>+</td>
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<td>31</td>
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<tr>
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<td>24</td>
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<tr>
<td>Tumble drier</td>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>18</td>
</tr>
<tr>
<td>Dish washer</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>218</td>
</tr>
</tbody>
</table>

* “+/-” for no/yes, “-” for very small number

Table 2: Potentials for household electricity demand as frequency controlled reserve. (Marcus-Møller, 2006)
reconnection. For compressor type of demand it is not possible to reconnect right after a disconnection. The typical compressor system in refrigerators and freezers are design so they need a minimum resting period of 5 minutes before they can be reconnected.

Many modern appliances are equipped with advanced electronic control. This can be helpful when the frequency control shall be installed. In some modern washing machines and tumble driers a possibility of stopping and delaying the process already exist. In these cases the cost of integrating the frequency control would be limited. In other cases, like water heater, a mechanical thermostat is used to control the temperature and higher investment cost for frequency control can be foreseen.

The average electricity consumption for an individual household appliance is limited. Average consumption varies from 22 W, for a high efficiency refrigerator, to 400 W for water heater in a four persons family. Electric space heating can be in the order of 1 to 2 kW/ per household (average over the year). Peak demand for electric heating is about 4 kW per household (as an average over many houses). In the EFFCOLOM project, only households with a electricity demand over 16,000 kWh/year was included and here the average peak demand was 5 kW per household.

Cost for traditional reserve are in the order of 25,000 – 100,000 €/MW/year. With an estimated large production cost of the frequency control of 20 € (PNNL, 2003), the specific cost would be 1,100,000 €/MW/year for the 22 W appliance and 25,000 €/MW/year for a 1 kW appliance (10 years life time and 5% p.a.) If an installation with electric heating would require 1 control unit per 400 W the specific cost would be 65,000 €/MW/year.

Monitoring
It is important for the stability of the electricity system to know the amount of reserve. However the traditional way of monitoring reserve with high quality real time measurements will not be realistic or needed in relation to a large number of small appliances.

For small appliances (e.g. the refrigerator, freezer or water heater) the cost for the investment of control system and the costs for monitoring would indicate that the transaction should be taken care of when producing and selling the appliance. The volume can not justify any monitoring activities for the individual appliances and this might not be needed if the control is integrated in the equipment and if the control cannot be deactivate. All new appliances could have the frequency control system installed or the consumer could choose appliances with or without the system. In the latter case a subsidy could be used to outweigh the cost of the control equipment. Monitoring of the actual reserve from small appliances could be done by monitoring the
sales and by detailed measurement for a small sample to indicate the variation during day and year. Lifetimes of appliances are well known from the national survey Elmodel-Bolig (average 10 to 15 years for refrigerators and freezers).

The same system could be used in relation to electric heating by installing the control in each individual heater. Due to the variation in the use of electric heating a larger sample with detailed measurement would be needed.

If the system should be used in relation to existing equipment and as an offer to the end user, monitoring must be able to deal with consumers deciding to participate. A system could include the following three steps:

- It could be registered when the user offered the demand as frequency controlled
- It could be registered when the TSO ordered the demand to be active as reserve
- When both the TSO and the user set the system to be active the electricity consumption could be measured and compensated accordingly. For most cases this could be a monthly value, and for a small sample it could be hourly values.

For electric heating such a system would make it possible for the TSO to order a desired amount of reserve and e.g. only using a part of the total electric heating in winter. With such a system a real market could be established. The payment could be a rebate set by the TSO (e.g. 25,000 €/MW per year would be 0.2 € cent/kWh). If more or less reserve are offered the rebate could be adjusted. Home automation systems connected to the internet that can perform these transactions, exist on the market.

**Demand in other sectors**

In other sectors than in the household sector non-essential demand can be found too, e.g. in the industry. The demands include electric ovens, ventilation systems, centrifuges and aerating at waste water treatment plants. It has been estimated that in Danish companies 96 MW can be interrupted with minimal notice of 5 sec. 71 MW can only be disconnected for 10 minutes and the rest for maximum an hour. These values are for Denmark as a whole although the majority may exist in West Denmark where most of the industry is situated. In these potential electric heating is not included. 270 MW (peak) is used for electric heating in trade and industry (Dansk Energi Analyse and Norenergi, 2005).

Uninterruptible Power Supply (UPS) could be another source of reserve. UPS exist in many sized (kW and MWh). Some have a battery time for more than 1 hour. Such systems could be used for frequency controlled reserve. The larger units already have control equipment for changing to battery operation at low frequencies. By increasing the set point to e.g. 49.9 Hz the UPS could work as reserve in up to 15 minutes. In UPS with a total battery time of less than 1 hour, less than 15 minutes could be supplied. Since many frequency drops have a very short duration (less than a minute) such a
resource would also help to improve the frequency quality. To obtain a secure operation extra programming could be helpful, e.g. to control that battery operation in under frequency situations only was maintained as long at a certain battery time still was available for the intended purpose.

1.4 Discussion

In next phase of this project a detailed design of the set point of the control system will be made. A starting point could be to use electric heating more actively than the compressor type of demand. Electric heating can be disconnected as often as needed, while the compressor type of demand requires minimum 5 minutes rest after a disconnection. Electric heating could be disconnected even in the normal frequency range and thereby provide primary control (e.g. linearly from 49.95 to 49.85 Hz). Compressor type demand could be used at a lower frequency range (e.g. linearly from 49.85 to 49.75 Hz) and with a five minutes delay for reconnecting. With a set point of 49.85 only five events happen per month. Per compressor this would mean one or two disconnection per month (assuming that the compressor is running one third of the time). As presented in PNNL (2003) the linearly activation can be achieved by varying the set point randomly at the individual appliances.

In this article the main focus has been on East Denmark, which is a part of the Nordel synchronous electricity system. If the frequency control system should be integrated into appliances from the factory it would be practical if manufactures could supply the equipment to the global (50 Hz) marked, or at least the European marked. The settings mentioned above would not harm to be used in the UCTE system – but the value for this type of reserve might be less than in smaller systems, like the Nordel system.

The technical potential for using demand as frequency controlled reserve exists. Some further work must be done to find the optimal combination of size of end use and the investment in control system. The smallest appliances, e.g. the high efficiency refrigerator, seem to be too small to justify the investment in control equipment.

To be able to use demand as reserve the procedures for contracting these reserve must be developed. E.g. high accuracy real time measurement is not needed and cannot be justified in relation to a large number of smaller demands. Contract forms must be developed, e.g. to include subsidy for integration control equipment in new appliances.

1.5 References in this chapter


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2
DYNAMIC SIMULATION OF CHOSEN CONCEPTS

2.1 Abstract
The objective of the work package 2 is to build up dynamic simulation models of demand as frequency controlled reserve (DFR), and integrate them with power systems to perform dynamic simulation studies and evaluate the technology.

A number of tasks are involved in this work package. Firstly, the control logic of DFR needs to be designed. Two types of controls have been developed, including type I-external control DFR which turn on and off the loads according to system frequency directly, and type II- integrated control, which turn on and off thermostatically controlled loads by adjusting their temperature set points according to system frequency. Both types can contribute to frequency control for under frequency events, and type II can also contribute to high frequency cases, which is comparable to generators.

Secondly, the simulation models of different DFR control logics are made in Power Factory software by DiGSIILENT. The thermostatically controlled loads have been focused in the project due to their cyclic on-off operation and considerable volume. The developed models contain explicitly the dynamical equations of thermostatic loads. Model parameters such as the rated power, the thermal capacity, the thermal conductance, and initial temperature etc. are made statistically distributed, in order to represent many such loads as realistic as possible. To ensure good performance and avoid any side effects, analyses have been performed to optimally design the model parameters that can affect frequency control.

Thirdly, the developed DFR models are integrated with several power system models, and simulation studies are performed to investigate DFR’s performance for frequency control. The power system models used include a simple one-bus system, a large scale interconnected system the Nordic system, and a small islanded system the Bornholm system. Contingency events including a sudden load increase and generation outages are simulated to evaluate DFR’s performance as frequency controlled disturbance reserve. Wind generation is also considered to evaluate DFR’s performance as frequency controlled normal reserve.
2.2 Understanding DFR for frequency control

The frequency of power system is determined by the power balance between supply and demand. When an imbalance occurs, caused by e.g. a generator outage, either generation or demand can be adjusted to recover the frequency as fast as possible. Up to date, system operators mainly utilize generation for frequency control, which could be expensive and unfriendly to our environment.

In fact, many demands in power systems are flexible in their way of electricity consumption. For example, household loads such as water and space heaters are turned on and off in cycles according to set points, and industrial loads such as water processing and UPS banks can be turned on or off for a reasonably long duration (>15 minutes) [1]. By designing properly the control logic, these loads can provide reserves to the system and contribute to frequency control.

Generally, the design of DFR can be differentiated into two groups, i.e. with and without communication systems. In the past, utilities have already implemented many kinds of load management programs for automatic or manual reserve. For example, a market based demand management program using low frequency relay to control industrial loads is developed by Gaz de France in UK [2]. A similar program is implemented in the New Zealand power system [3]. In Finland, 1000 MW industrial demands from wood processing, chemical and metal industrials are used as frequency controlled as well as manual reserve [4]. These programs focused on large size industrial loads, and have communication system between system operator and the controlled load. The advantage of such design is that the operator will have clear idea of the amount reverses from demands. Another load control program implemented in New Zealand is so called ripple control, which actually turn on in the night (low price period) or off in the day (high price period), the electric appliances like water heaters, so that electricity cost can saved [27]. The ripple control is aimed at levelizing the energy consumption by proper economic incentive and only a timer and a properly rated contactor are needed in this type of control. In contrast, the DFR technology in the project focuses on providing reserve from demands to ensue secure operation of power systems. Certainly, the synergy of the two technologies and perhaps with more others is possible and interesting for research, but is however out of the scope of this project. The project team has planned to investigate into this direction in the future.

A pilot project using the ComfortChoice technology for controlling air conditioners to provide reserve was carried out by the Long Island Power Authority in 2003 [28]. Due to the communication (two way paging) system introduced, the reserve is to be activated relatively slow in about 90 seconds.

The Pacific Northwest National Laboratory (PNNL) has suggested that individual household appliances suitable for temporary disconnection can provide fast reserve that can react within seconds without communications, e.g. refrigerators and air conditioners
Similar suggestions have been made in UK [14]. The idea was presented as early as in 1979 [29]. The recent availability of low cost micro electronics makes these ideas attractive.

The previous research works have achieved many useful results. Based on those previous works, the DFR in this project is to be designed without communication, and respond autonomously to locally measured frequency. Such a design will allow the implementation of complicated control logics into the load controller, the activation speed won’t be sacrificed compared to if appliances are controlled centrally though a communication system. This is more practical for use of many small size loads, which have a considerable volume when aggregated together. For example, the potential of DFR compatible loads in Eastern Denmark, based on household space and water heaters and refrigerators etc, is about 218 MW which surpasses the Nordel requirement of 100 MW for frequency controlled disturbance reserve [5] [6] [7]. The demands that can be used in the technology are extended to proper loads from all sectors, such as households, industrials, and business sector. Table 1 gives a summary of major load management programs in implementations and comparisons with the DFR technology developed in this project.
<table>
<thead>
<tr>
<th>Name</th>
<th>Aim and markets to participate</th>
<th>Target demands</th>
<th>Technology</th>
<th>With communication?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load shedding program in Finland</td>
<td>Provide reserve, ancillary service market</td>
<td>Large industrial loads</td>
<td>Automatic or manually controlled by system operators</td>
<td>No</td>
</tr>
<tr>
<td>Load shedding in New Zealand</td>
<td>Provide reserve, ancillary service market</td>
<td>Large industrial loads registered as interruptible</td>
<td>Controlled by receiving the ‘broadcast’ signal from system operator</td>
<td>Yes</td>
</tr>
<tr>
<td>Gaz de France</td>
<td>Provide reserve, and load reduction, both ancillary service and energy market</td>
<td>Industrial loads participated in schemes</td>
<td>Two different systems/services, for frequency response and energy reduction. The monitoring is included in the frequency response scheme therefore communication is needed</td>
<td>Yes</td>
</tr>
<tr>
<td>ComfortChoice Technology</td>
<td>Provide reserve, ancillary service market</td>
<td>Air-conditioners</td>
<td>Central controlled appliances, respond to low frequency in 90 seconds</td>
<td>Yes (2 way paging system)</td>
</tr>
<tr>
<td>Ripple control in New Zealand</td>
<td>Peak load reduction and electricity cost saving, energy market</td>
<td>Deferrable demands e.g. hot water heaters etc</td>
<td>Local control by a timer and contactor</td>
<td>No</td>
</tr>
<tr>
<td>Grid Friendly (USA)</td>
<td>Provide reserve, ancillary service market</td>
<td>Various household appliances</td>
<td>Local control with frequency sensor, fast responding speed</td>
<td>No</td>
</tr>
<tr>
<td>Technology similar to Grid Friendly (UK)</td>
<td>Provide reserve, ancillary service market</td>
<td>Mainly refrigerators and freezers</td>
<td>Local control with frequency sensor, fast responding speed</td>
<td>No</td>
</tr>
<tr>
<td>DFR (in this project)</td>
<td>Provide reserve, ancillary service market</td>
<td>Domestic and industrial loads</td>
<td>Local control with frequency sensor, fast responding speed, advanced control logics and potential synergy with other demand technologies</td>
<td>No</td>
</tr>
</tbody>
</table>

The mechanism of DFR can be understood by studying the on-off control of active load for damping electro-mechanical oscillation in the one-machine-infinite-bus system (OMIB) [8] [9]. Consider a OMIB system in Figure 1 where $P_{load}$ is an active load and responds to the rotor speed variation of $G1$ according to Figure 2, i.e. $P_{load}$ is turned off.
and on when \( \omega \) of \( G1 \) falls below a threshold and rises above another threshold. The equilibrium of the system is determined according to Equation (1) = 0, e.g. the point ‘a’ in Figure 3 where the mechanical and electrical power curves intersects.

\[
\begin{aligned}
\frac{d\omega}{dt} &= \frac{\omega}{2H} (P_m - E_1^' E_2^' \sin \delta - P_{load}) \\
\frac{d\delta}{dt} &= \omega - \omega_s
\end{aligned}
\]

(1)

**Figure 1** The OMIB system with on off control of an active load \( P_{load} \).

- \( H \) G1 acceleration time constant
- \( \omega \) G1 rotor angular speed
- \( \omega_s \) synchronous speed
- \( P_m \) mechanical power applied to G1 shaft
- \( E_1^' \) G1 transient internal voltage
- \( x_d \) G1 internal transient reactance
- \( \delta \) is \( E_1^' \)'s angle with respect to common system reference
- \( E_2 \) voltage of infinite generator G2
- \( x_e \) equivalent reactance of the transmission line

The behavior of this system after a small disturbance, e.g. a sudden increase of mechanical power \( P_m \) or short-circuit fault at \( G1 \) terminal bus that are cleared immediately afterwards, can be analyzed by the equal-area criteria:

- Without on/off control of \( P_{load} \) and if the disturbance is small enough, the \( G1 \) will oscillate periodically around the initial equilibrium point \((\omega_0, \delta_0)\)^T in the \((\omega, \delta)\)^T space since the system has no damping. As shown in Figure 3, the oscillation travels clockwise around \((\omega_0, \delta_0)\)^T and the radius is determined by the amplitude of the disturbance initially, i.e. the horizontal distance between ‘a’ and ‘b’ in Figure 3. On the other hand, the oscillation centre i.e. \((\omega_0, \delta_0)\)^T is determined by initial equilibrium. E.g. with \( P_{load} \) on and off initially, the equilibriums correspond to \((\omega_0, \delta_{on})\)^T and \((\omega_0, \delta_{off})\)^T respectively as shown in

**Figure 2** the on-off control logic of \( P_{load} \) according to \( G1 \) rotor speed.
the upper plot of Figure 4, which consequently determines two different groups of oscillation trajectories after the disturbance.

- With $P_{\text{load}}$ controlled according to Figure 2, and assume no time delays in disconnection and reconnection, after the disturbance the oscillation of $G1$ will be shifted between two groups of trajectory (with centers at the two equilibriums respectively) when $\omega$ crosses the horizon axis every time. This actually results in the reduction of oscillation amplitude as shown in the lower plot of Figure 4, and consequently the oscillation will be damped out constantly.

In Appendix A, a simulation model of the OMIB with on-off load control in Figure 1 has been built using MATLAB/Simulink. Simulations with the model have verified the analyses above. In a multi-machine system, individual machine can be considered as a $G1$ connected to the rest of the system, the on/off load control according to rotor speed is equivalent to according to system frequency, and the oscillation of frequency after a disturbance will be damped in the same way as analyzed above. Direct applying the on/off strategy for frequency control is not realistic, since it will require very fast switching operation which is not appropriate for many loads in practice. However, it provides the theoretical foundation for proper design of demand as frequency controlled reserve.
2.3 Design of DFR Control Logic

Type I – External Control
The type I DFR i.e. external control type disconnects and reconnects electric appliances e.g. a water heater to the grid when system frequency falls and recovers respectively [10] [11] [12]. In this type, it is assumed the thermostat of the DFR loads has no memory, i.e. the load will be turned on immediately when the power supply is reconnected e.g. after the frequency recovers.

The disconnection set point should be designed according to the type of reserve which the DFR targets to provide, e.g. 49.90 and 49.95 Hz for frequency controlled Disturbance and Normal reserves respectively in the Nordic system. To prevent over activation of reserve from DFR, it is also necessary to design the disconnection set points of many such appliances to be different from each other as in Figure 5. Particularly, if the set points of many DFRs with similar capacities are designed according to a uniform distribution over a small range e.g. 49.85–49.90 Hz, the reserve can be proportionally activated in a low frequency event which meets the requirements of the Nordic code [5].

The reconnection set point should be higher than the disconnection set point to provide a dead-band. This is to prevent DFR from oscillatory behaviors, e.g. 49.90 Hz for disconnection and 49.95 Hz for reconnection respectively [13].

![Figure 5 Design of proportional activation for DFR Type I](image)

Table 2 Design considerations for DFR Type I Parameters

<table>
<thead>
<tr>
<th>DFR Parameters</th>
<th>Design considerations</th>
</tr>
</thead>
</table>
| Disconnection set point $f_{\text{off}}$ |  - According to target reserve, e.g. from 49.50–49.90 Hz for frequency controlled disturbance reserve  
  - Random distributed for many DFR appliances |
| Reconnection set point $f_{\text{on}}$ |  - Ensure frequency recover to normal range  
  - Different from $f_{\text{off}}$ to provide a dead-band and prevent oscillatory behaviors of DFR, e.g. 49.95 Hz  
  - Reduce wear outs to appliances |
| Disconnection delay $T_{\text{off}}$ |  - Due to frequency measurement and should be as short as possible for fast response |
Consider if the demand/appliance can be switched frequently or not, since many low frequency events are short in duration, and intervals between events can be very short sometimes [1].

Reconnection delay $T_{on}$

- Random distributed for many DFR appliances to prevent simultaneous reconnections. Some appliances require a resting period, e.g. 5-30 minutes. A (too) long delay may cause instability.

Time delays are involved in disconnection and reconnection. The delay in disconnection is mainly due to frequency measurement and should be made as short as possible for fast response. The reconnection delay is due to many reasons. First, it is to reduce the wear out to the appliance caused by frequent switching. Second, the time delays of reconnection of many DFRs should be different to prevent all appliances from reconnecting to the grid at the same time. Certainly, separated reconnection can also be realized by using different reconnection frequency set points, but not considered in this project. The Table 2 provides a summary of design considerations for parameters of DFR Type I-variant design for thermostatically controlled loads.

Thermostats typically operate with a hysteresis, e.g. a 2°C difference between $T_{high}$ and $T_{low}$. When the temperature is between these values the appliance can be on or off. The status is determined by the history – a kind of control memory, i.e. what happened last? Was the appliance turned on or off? The control maintain the status until the temperature meets one of the two temperatures, $T_{high}$ and $T_{low}$.

In relation to DFR Type I, three different designs of the reconnection exist:

<table>
<thead>
<tr>
<th>Type</th>
<th>How does the control start after reconnection?</th>
</tr>
</thead>
<tbody>
<tr>
<td>I_a</td>
<td>Keep the current status</td>
</tr>
<tr>
<td>I_b</td>
<td>Always start on</td>
</tr>
<tr>
<td>I_c</td>
<td>Always start off</td>
</tr>
</tbody>
</table>

The type I_a could be a mechanical thermostat, while the type I_b and I_c could be programmed electronic thermostats. In this report, the simulation models of Type I_a and I_b have been made in Power Factory. Type I_c model will be developed in the future.

Besides different reconnections for Type I, the disconnection can also be implemented differently for special type of appliances e.g. Danfoss floor/water heaters and heat pumps. These appliances have a special input for external control of temperature set.
points. Thus the disconnection can be realized by step changing the temperature set points according to system frequency, e.g. from 60 °C to 0 °C when frequency drops below 49.90 Hz, and from 0 °C to 60 °C when frequency recovers above 49.95 Hz.

What variant design is selected will have consequences for the type of reserves that DFR can deliver. This is studied in the next chapters. Simulations show that the type I b without appropriate design can create over swing in the frequency, and cannot be recommended.

**Type II-integrated control**

Similar to the variant designs of Type I, Type II control is dedicated for thermostatically controlled loads e.g. electric heaters and refrigerators. In stead of tripping loads directly, the temperature set point will be varied dynamically according to frequency [10] [14]. For example, the temperature set points of heaters can be controlled according to Equation (2),

\[
T_{\text{high}} = T_{\text{high}}^{\text{normal}} + kf (f - f_0) \\
T_{\text{low}} = T_{\text{low}}^{\text{normal}} + kf (f - f_0)
\]  

(2)

where \(T_{\text{high}}^{\text{normal}}\) and \(T_{\text{low}}^{\text{normal}}\) are nominal high and low set points (and defining the hysteresis of the control), \(f_0\) is system nominal frequency e.g. 50 Hz for the Nordic system, \(f\) is actual system frequency, and \(kf > 0\) is the coefficient of frequency change.

Consider a large number of Type II heaters connected to the grid for enough long time, their temperatures should distribute evenly among the upper and lower temperature set points. The percentage of on/off units (\(on\%\) and \(off\%\)) will also become stable, so as the total power consumption. If the frequency drops/increases by \(\Delta f\), the initial power reduction/increase from these loads can be approximated using Equations (3) and (4) respectively,

\[
\frac{kf\Delta f}{T_{\text{high}}^{\text{normal}} - T_{\text{low}}^{\text{normal}}} \times \text{TotalMW} \times on\% \\
\frac{kf\Delta f}{T_{\text{high}}^{\text{normal}} - T_{\text{low}}^{\text{normal}}} \times \text{TotalMW} \times off\%
\]

(3)  

(4)
The integrated control will be less disturbing for the end-user because it is only adjusting the length of on or off cycles of the loads. If the frequency falls, the control will first start disconnections with those appliances that are close to the end of their on cycle. This is illustrated in Figure 6, where the left side shows the situation where the grid frequency is 50 Hz and totally 10 heaters units with integrated control are on (red dots with up arrows), and the right side shows in the next moment the grid frequency goes below 50 Hz, the temperature set points are changed accordingly, resulting in only 7 on units. The number of units that are off, and therefore the power, is proportional to frequency drop, if assuming that initially those loads are uniformly distributed between high low temperature set points.

It can be seen that reserve from integrated control DFR is realized by aggregating many of such appliances. Therefore, it will not significantly increase the wear outs of individual appliances. The integrated control is functioning for all kinds of frequency deviations, including large deviations in low and over-frequency events, and small deviations in normal frequency range. This makes the integrated control very ideal for frequency controlled normal reserve. Especially for a system with high penetration of fluctuating renewable generation, such as the Bornholm power system in islanded operation mode [15] [16], the integrated control of DFR should be able to improve frequency stability under normal conditions with the presence of wind generation.

**Comparisons of DFR control logics**

Type I control logic is equivalent to the simple on/off load control except for the time delay in reconnection and the control signal used. Due to the reconnection delay, Type I mainly contributes to damp the first cycle of oscillation, especially if the oscillation does not last long enough.

The type II extends the damping to over frequency events and is able to provide continuous regulations. Since the control is obtained by aggregating many such units, units that are just turned off will not be turned on again shortly afterwards and vice versa (because of their internal thermodynamics). This indicates continuous frequency variation would not result in continuous wear out to individual appliance.

---

**Figure 6 Illustration of Type II DFR control logic**

---
Type II DFRs may not be fully activated when needed if $k_f$ in Equation (2) is not properly designed. Proper design of $k_f$ should be based on the specific reserve in target. Alternatively, different $k_f$ values can be designed for different level of frequency deviations. For example in Figure 7 (b), a smaller coefficient is used for frequency between 49.90~50.10 Hz under normal operation, and a bigger coefficient is used for disturbance with large frequency deviation (>0.1 Hz) to ensure as many units as possible can be turned off. In this project, only single coefficient is considered for the type II, and multiple coefficients will be investigated in the future. Table 4 gives the comparisons of DFR control logics developed in this project.

![Figure 7 DFR II control logic for integrated control](image)

(a) Single coefficient
(b) Multiple coefficients, smaller for normal conditions, larger for disturbances

[Why not make the y-axis delta P, and show values for negative x as negative values. This would be much better for my understanding]

<table>
<thead>
<tr>
<th>Table 4 Comparisons of DFR control logics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type I</strong></td>
</tr>
<tr>
<td>Control logic</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Advantage</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Disadvantage</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
2.4 Modeling of DFR heaters in DlgSILENT Power Factory

Electrical heaters are focused in modeling of both Type I and II DFR in this project. These heaters including space and water heaters with DFR control logics are implemented in DlgSILENT using the composite modeling approach [10] [17]. The mathematical equation describing electric heater’s thermodynamics is given by,

$$C \frac{dT}{dt} + G(T - T_a) + P_{disturbance} = w \cdot P$$

where,
- $C$ is the heat capacity of the heating mass
- $G$ is the thermal conductance between heated and non-heated mass
- $P$ is the heater power
- $T$ is the temperature of the heated mass
- $T_a$ is the ambient temperature
- $w$ models hysteresis, i.e. if $T > T_{high}$, $w = 1$ - “on” stage
  if $T < T_{low}$, $w = 0$ - “off” stage
  else $w = w$

$P_{disturbance}$ is customer’s influence on the heater’s dynamics, e.g. consumption of hot water for water heaters.

The temperature set point i.e. the midpoint between $T_{high}$ and $T_{low}$, is determined according to the type of heaters, e.g. 20 and 55 degrees for space and water heaters respectively. The difference between $T_{high}$ and $T_{low}$ is set to 2 degrees for all heaters. The uncertainties of initial temperature and on/off status i.e. $T_0$ and $w_0$ are modeled by random numbers within $[T_{high}, T_{low}]$, and 0/1 respectively.

The thermodynamic parameters of these heaters such as rated power and heating capacity are diversified to ensure the model as realistic as possible. Table 5 summarizes the methods for modeling variations of heaters parameters in the developed model. The voltage and frequency dependencies are not included in current model but will be investigated in the future.
Table 5 Modeling of heater parameters variations

<table>
<thead>
<tr>
<th>$C$</th>
<th>$G$</th>
<th>$P$</th>
<th>$P_{\text{disturbance}}$</th>
<th>$T_0$</th>
<th>$w_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal distribution</td>
<td>Normal distribution</td>
<td>Normal distribution</td>
<td>White noise and $P_{\text{disturbance}} &gt; 0$</td>
<td>Rand $[T_{\text{low}}, T_{\text{high}}]$</td>
<td>Randomly chosen e.g. 30% of units 'on' initially</td>
</tr>
</tbody>
</table>

The structure of the developed model consists of several functional blocks, including blocks for frequency measurement, thermo dynamics, DFR control logic, and hysteresis etc. Figure 8 shows the structure of the developed DFR models.

The developed DFR model aggregates many electric heaters inside. Theoretically, the heaters in one such model can be as many as possible. The advantage of the developed model is that every heater is modeled using a specific dynamic equation, considering variation of parameters. Besides, external disturbance due to e.g. user consumption of hot water is also included. However, such detailed modeling also creates the limitation as the simulation speed is affected very much by the number of heaters. An amplification factor is added to the output power of the model, so that it can produce the demand of more heaters than the actual number. This is a tradeoff in order to simulate as many heaters as possible while not overly increasing the computational load. To make this tradeoff reasonable, the actual number of heaters inside is set to a large number, i.e. 500 heaters per model. To overcome the limitation of the developed model, other modeling approaches based on, e.g. system identification or statistical modeling [18] [19] [20], can be investigated in the future.

![Figure 8 Structure of DFR heater models in DiGILENT](image-url)
2.5 Optimal design of DFR parameters

For implementation of DFRs, the parameters that affect their frequency control capability should be designed to ensure optimal performance for all kinds of scenarios in consideration. These parameters include $f_{off}$ and $f_{on}$ for type I, and $k_f$ for type II. Among them, $f_{off}$ and $k_f$ are critical and have impacts on others. E.g. the reconnection set points $f_{on}$ can be determined as $f_{off}$ plus a small dead band, and should be designed according to considerations, such as to avoid simultaneous reconnection etc.

A number of scenarios are to be simulated for comprehensive assessment of DFR’s performance, including

- base case - one bus simple system, with step change(increase) of load
- islanded operation cases - Bornholm power system, with a generation outage and with wind generation under normal operation
- Interconnected system case - the Nordic system, with a generation outage

For contingencies, i.e. sudden load increase and generation outage, the objective of DFR is to provide disturbance reserve and to be activated when frequency falls within [49.50, 49.90] Hz. Therefore,

- For type I DFR, $f_{off} \leq 49.90$ Hz and with small deviations within [49.5-49.9] Hz between different heaters to avoid overshoot of reserve.
- For type II DFR, $k_f$ can be selected to ensure all appliances to be turned off when frequency falls below 49.90 Hz, i.e. $|\Delta f| \geq 0.1$ Hz. This equals to move the high temperature set point to the normal low set point. The difference between high and low temperate set points is 2 degrees in the developed heater models, $k_f$ can be therefore determined to 20 °C/Hz according to Equation (1). This value is actually the upper boundary of $k_f$ for DFR II as disturbance reserve, and of course can be adjusted according to other considerations such as coordination with reserves from other sources etc. For example, if we would like DFRs to respond only to more serious events and all of them to be off at a larger frequency deviation, e.g. 49.50 Hz, the $k_f$ should be 4 °C/Hz.

For normal operation cases, i.e. Bornholm system with wind, the objective of DFR is to provide normal reserve for frequency within [49.90, 50.10] Hz according to the Nordic code [5]. In fact, the normal frequency range for Bornholm in islanded operation could be less strict, e.g. [49.85, 50.15]. Therefore

- For type I DFR, $50 > f_{off} \geq 49.90$ Hz or lower and with small differences among heaters to avoid overshoot
For type II DFR, \( k_f \) should ensure most of the appliances can be turned off or on
before frequency out of normal range \([49.90, 50.10]\) Hz, i.e. \(|\Delta f| < 0.1\) Hz.
Consequently, \( k_f \geq 20 \, ^\circ\text{C/Hz} \) or a lower value.

Table 6 below summarizes DFR parameters for simulation studies in Section 6. Type I
DFR is not considered for Bornholm system in normal operation with wind case, but
will be studied in the future.

**Table 6** Design of DFR parameters \((f_{off}, f_{on}, T_{off}, T_{on}, k_f)\) in simulation cases
(Rand[min, max] stands for uniform random distribution within [min, max]).

<table>
<thead>
<tr>
<th>Simulation Cases</th>
<th>Design for DFR parameters</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case-Single bus connected with DFR loads</td>
<td>DFR objective</td>
<td>Type I (and the variant)</td>
</tr>
<tr>
<td>Sudden load change</td>
<td>Disturbance reserve</td>
<td>( f_{off} : \text{Rand} , [49.85, 49.90] ) Hz (can be a larger range e.g. ([49.50, 49.90]) Hz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( f_{on} : 49.95 ) Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{off} : 0.4 ) s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( T_{on} : \text{Rand} , [4, 6] ) min</td>
</tr>
</tbody>
</table>

| Bornholm system in islanded operation | No wind with contingency | Disturbance reserve | Not considered in this report | \( k_f = 20 \, ^\circ\text{C/Hz} \) |
| Normal operation with wind | Normal reserve | | |

| Nordic interconnected system | contingency | Disturbance reserve | \( f_{off} : \text{Rand} \, [49.85, 49.90] \) Hz (can be a larger range e.g. \([49.50, 49.90]\) Hz) | \( k_f = 20 \, ^\circ\text{C/Hz} \) |
| | | | \( f_{on} : 49.95 \) Hz | |
| | | | \( T_{off} : 0.4 \) s | |
| | | | \( T_{on} : \text{Rand} \, [4, 6] \) min | |

The above discussion of optimal DFR parameter design is based on system
requirements, i.e. the technical specifications of the targeted reserves. In fact, a
comprehensive design should also consider the technology’s impact on the operation of
the candidate appliances. In our future research, evaluation of DFR’s impacts on
appliances’ operation will be performed using historical system frequency data.
Accordingly, optimal design of DFR parameters may be re-preformed.
2.6 Dynamic Simulation

The DFR heater models including DFR Types I, i.e. the variant designs I_a and I_b, and II have been developed using DIgSILENT Power Factory and are to be studied in simulations. As introduced in Section 5, several cases are considered in simulations to examine DFR as disturbance or normal reserves. In addition, penetration studies i.e. simulations with different percentages of DFR loads versus total system demand, have also been performed.

Model parameters in simulations

One DFR heater model contains 5 groups of heaters, and each group contains 100 heater units. In each group, thermodynamic parameters including $P$, $C$, and $G$ are normally distributed with mean values of 3, 3, 4, 5 and 5 kW respectively. Without scaling, the total installation capacity of all heaters is approximately 2.0 MW. The initial status of heaters are modeled as random values, i.e. for a single unit

- $w_0$ is randomly assigned 0 or 1 and initially 70% of heaters are assumed ‘off” i.e. $w_0 = 0$;
- and $T_0$ is a random value within $[T_{low}, T_{high}]$;

Figure 9 Initial statuses of heaters inside one DFR model (500 heaters): Red dots represents units in ‘on’ cycle and blue dots represent units in ‘off’ cycle

Total installation capacity $\approx 2.0$ MW, and total power of initially ‘on’ heaters $= 2*$(1-70$\%$) $\approx 0.6$ MW
Figure 9 presents the initial status of 500 heaters inside one DFR model, where x-axis is the rated power of heaters in kW, y-axis is the heater group number inside the model, z-axis is the heater temperature. Because different heater groups have different temperature set points (for space and water heaters), all temperatures in Figure 9 have been scaled into the same interval.

The model parameters that affect the DFR function such have been designed according to analyses in Section 5. Figure 10 presents the distribution and cumulative capacity versus corresponding \( f_{\text{off}} \) for the developed type I (and its variant) model. The cumulative capacity is actually the maximum available reserve and is proportional to frequency drop, which resembles the droop control of a generator. Figure 11 is the distribution of heater power \( P \) versus reconnection delay \( T_{\text{on}} \) for the developed type I (and its variant) model, where the cumulative capacity over the time delay is actually the maximum ‘return energy’ after frequency recovers, and is proportionally increased to avoid simultaneous reconnection.

2.6.1 Base case – a simple one-bus system integrated with/out DFR load

In the base case, a simple system in Figure 12, which consists of an ‘External Grid’, one bus and one DFR load model ‘DFRLoad’, will be simulated. The ‘External Grid’ in DIgSILENT is a simplified generator model. The acceleration time constant (H) of the ‘External Grid’ is set to 200 s. Since the heaters are affected by two factors, the system frequency and the internal thermodynamics, a long simulation time can be needed before the output power can get (relatively) stable, if any of the two are changing frequently and continuously. Therefore a high time constant representing a large size system is used for the simplified system in order to reduce the impacts of system frequency on the DFR model, so that a short simulation time is needed before it can get stable. The base case is to study the basic characteristics of the developed DFR models,
e.g. the typical output level of power consumption etc. Therefore the high time constant value is acceptable in this context. The bus is set as ‘slack’ type, i.e. the active and reactive generation will be automatically balanced to the load. The scaling (amplification) factor for the output power of the DFR model is 5, therefore total installation capacity is about 10 MW. 70% of heaters are assumed off initially, equivalent to 3 MW heater load connected to the grid.

**Figure 12 The simple power system in Base Case study**

**Normal operation condition**

The developed DFR mode is to be integrated with the simple system and simulations will be performed with/without DFR function under normal operation conditions. Only DFR II generates different simulation result for DFR function enabled case. The DFR I (variants Ia and Ib) and DFR disabled cases produces very similar results except for little difference caused by the random noise included in the model. Figure 13 presents the system frequency and demand of the DFR load for with/out DFR II.
Figure 13 Comparisons of frequency and DFR load demand with/without DFR II function under normal operation

It is observed,

- With DFR II enabled, the load power is reduced (to provide reserve) at the beginning of simulation, therefore helping to improve the frequency quality. E.g. at $t=88.7$ s, the output power with/out DFR are 2.165 MW and 3.112 MW, and the frequencies are 49.989 Hz and 49.965 Hz respectively.
- In both cases, system frequencies will become stable at around the same value 49.964 Hz after 800s or so.
Figure 14 Temperatures of the same heater group with/without DFR II under normal operation

Figure 14 shows the temperatures and set points of the same heater group (100 units) for the simulation in Figure 13. The temperature set points of DFR II is continuously varying according to the frequency during the simulation, resulting in the change of output power accordingly.
A step increase of load
In this case, a sudden load increase of 30 MW will be simulated at t=1000s during the total simulation period of 4000s. The sudden load increase may not be realistic in reality, but it can provide a good case for benchmark study of DFR’s performance.

Figure 15 shows the simulation results of system frequency and the power of DFR load with three types of DFR respectively. The simulation result without DFR is also added for comparison. Figure 16 shows 100s after the load event. It is observed that,

- With DFR function and after the load event, the demand of all types of DFR is effectively reduced, and consequently the system frequency stops going down at about 49.85 Hz for duration of at least 800 s. In contrast without DFR and after the event, the system frequency dips to a lower value of about 49.83 Hz.
- DFR I (I_a and I_b) produce similar results despite little differences due to the random disturbance included in the developed model. While DFR II is faster in reducing its output power during the event, therefore a slightly higher frequency is observed right after the event. This can be explained due to continuous adjustment of temperature set points by DFR II. Other DFRs will only respond when frequency drops below the pre-set set point.
- The demand of the DFR II begins to return around 800s after the event due to the thermodynamics of heaters. The demand of DFR I_a and I_b do not return, since the system frequency has not recovered to the pre-set reconnection set point of 49.95 Hz.

In Figure 15, the DFR II demand begins to return from 800s after the contingency, and reaches approximately same level as before the contingency in about 2200 s later. According to the Nordic Grid Code [5], the automatic frequency controlled reserves should be active for maximum 15 minutes (900 sec). After 15 min. the manual reserves should take over. The simulation results of Figure 15 indicate that all DFRs are able to meet the requirement of the automotive reserve.
Figure 15: System frequency (upper plot) and the power (lower plot) of DFR model during the load event.
The DFR I and I_b have quite similar performance in above simulation case. In fact, the two types should differ from each other in the reconnection process as analyzed in Section 3. To visualize the difference, the simulation in Figure 15 is repeated, but with the load event cleared at t =1200s. Figure 17 shows the new result, where

- DFR I and its variant begin to reconnect to the system when frequency recovers above the pre-set set point and after certain time delay. While the demand of DFR II begins to pick up almost instantly when the frequency rises back.
- The DFR I has a larger ‘return energy’ than its variant design, resulting in a bigger frequency oscillation after the event clearance. While the demand of DFR II seems smoother than other types, so as the resultant frequency.

Figure 18 presents the temperatures of the same water heater group (100 units) during the event, where the difference of heater behaviors caused by different DFR control logics can be clearly seen.
Figure 17 System frequency (upper plot) and the power (lower plot) of the DFR model during the load event cleared afterwards.
Figure 18 Comparison of heater behaviours of the same group in DFR $I_b$ (Upper) and $I_a$ (Lower) and DFR II (next page) with a load event started at $t=1000s$ and cleared at $t=1200s$. The reconnection takes place between 1340 and 1860 because of the 4-6 min. reconnection delay.
**Conclusions from this section**

Several conclusions can be drawn based on the simulation results in this section:

- The DFR model, including all three types, is stable when integrated with a simple power system under normal and contingency (a load event) conditions.

- During the load event, all DFR types can help to improve frequency stability. DFR II is faster in disconnecting the heater load (because it reacts on any drop in frequency), while DFR I$_a$ and I$_b$ have similar performance in the disconnection procedure.

- After the load event, the demand of DFR II will eventually come back. The demand of DFR I$_a$ and I$_b$ will not be back until the frequency recover above the set point and after certain time delay. If the frequency recovers after a contingency, the DFR I$_b$ can have a larger ‘return energy’ therefore may cause a bigger frequency oscillation compared to other DFRs.

- All DFRs can meet the requirement of maximum 15 activation for automatic reserve in the Nordic system.
Second case: Nordic interconnected system integrated with/out DFR load under contingency condition

A contingency of 400 MW loss of generation

In the second case, the DFR model is to be integrated with a large scale practical power system to test its performance as disturbance reserve. The Nordic interconnected system model supplied by Danish TSO Energinet.dk is used. The model consists of 320 buses, and 125 synchronous generators, covering Sweden, Finland and Norway, and the Eastern Denmark. Figure 19 shows the Nordic system model where Eastern demark is not graphically shown.

The total system demand is set to 40 GW (peak load of the Nordic system is about 70 GW) in the simulation study. Five identical DFR models, i.e. 2500 heater units (installation capacity=5x2=10 MW), are connected with the system at five different, arbitrarily selected buses, which are denoted by purple circles in Figure 19. The parameters of these models are as introduced in Section 6.1. A scaling factor of 100 is applied to the output power of these models, so that the total installation capacity of the DFR heaters is 1000 MW, which equals to the required amount of frequency controlled disturbance reserve in the Nordic system. Note the actual power from the DFR loads in simulations is not necessarily equivalent to the required amount of reserve, since the heaters are operating in cycles. The DFR capacity used here is just for benchmarking purpose. The actual volume of DFR compatible loads in the Nordic is larger than this value, e.g. the Eastern Danish system, which is a small part of the whole Nordic and requires 100 MW disturbance reserve [5], alone has a potential for DFR of approximately 218 MW according to a survey in 2001 [1] [7] In Sweden and Norway, higher potential is available due to electric heating [30].

Totally four simulation cases have been performed for all heaters with 3 types of DFR respectively and without DFR at all. In order to study the impact of DFR installation location on simulation results, an additional case with DFR type II loads concentrated at the bus where DFR load 2 in Figure 19 is connected is simulated. All simulations have been performed for 3000 seconds, and a generator event of a 400 MW reduction at bus 5600 SOUTH3A (blue circle in Figure 19) is triggered at t=1500 s to study system response. Figure 20 shows the system frequency and the output power of one same DFR model in all simulation cases. Figure 21 is the same plot with zoom in of first 100s after the contingency.
Figure 19 The Nordic system model (without Eastern Danish part shown)

a. The purple circles denote where the DFR loads installed
b. The blue circles denote the contingency generator
Figure 20: System frequency (upper plot) and the power (lower plot) of the DFR model during the generator event.
Figure 21 System frequency (upper plot) and the power (lower plot) of the DFR model during the generator event (zoom in the 1st minute after the vent)
The average and standard deviation of frequency error have been calculated, and presented together with the lowest observed frequencies in Figure 22. The frequency error is calculated using the equation below:

\[
\text{Frequency error} = |\text{simulated frequency} - 50| \text{ Hz}
\]

Several interesting observations are found in these results:

- Before the contingency, the system frequency and demand of the DFR load are just slightly different for all cases, except for the beginning part of the simulations. After the contingency, system frequency will decrease and can recover eventually to the normal range in all cases (due to sufficient reserves inside the system), however, with different oscillations and lowest observed frequencies etc during the transition.

- The case without DFR has the largest frequency deviation caused by the contingency and latest observation time, i.e. minimum \(f = 49.867\) Hz at 10.0 s after the event. The DFR II including distributed and concentrated cases have the smallest deviation and earliest observation time, i.e. minimum \(f \approx 49.92\) Hz at 7.0 s after the event.

- Very small difference is observed for DFR II concentrated and distributed cases in terms of average and standard deviation of frequency error and lowest frequency. Certainly, DFR II concentrated and distributed cases differ in the power flows in the system, because different flow can generate different losses.

- For DFR I, the system frequency and DFR load power are approximately identical after the contingency for a short duration up to about 100 s. However, the DFR I \(b\) has a larger peak of ‘return energy’ at about \(t = 1900\) s than its variant design, and the system frequency accordingly oscillates to a lower value.
Consequently, very small difference is observed for DFR I_a and I_b in terms of average error and lowest frequency, while the standard deviation of DFR I_b is slightly higher.

Some of the observations actually echo those in Section 6.2, e.g. larger ‘return energy’ of type I. Again, the better performance of DFR II e.g. higher lowest frequency and smaller average and standard deviation of frequency error is attributed to the continuous variation of temperature set point, therefore a faster reduction of output power is observed. While DFR I and its variance will only respond when frequency below a preset threshold, i.e. 49.90 Hz in this case.

In Figure 23, the on-off cycles of the same heater unit in all cases are presented. Comparing the DFR disabled case with the rest, it can be seen that in a practical power system, the DFR control logics will not turn off electric heaters infinitely (therefore the discomfort to customers is limited) in event of a contingency. In stead, they will coordinate the operation cycles of heaters in a better way, in order to help recover the frequency.
Figure 23 On/off cycles of the same heater unit in all simulation cases with a generation contingency at $t=1500s$

a. Comparing DFR disabled case with the rest - DFRs do not stop appliances infinitely
b. Comparing DFR II distributed with concentrated cases, nearly no difference is observed
c. Comparing DFR $I_a$ and $I_b$, they are identical in disconnection but $I_a$ has extra delay in reconnection

Conclusions from this section

From the results in this section, it can be concluded that

- The developed three types DFR model (with a large number of heaters) is stable when integrated with a large scale practical power system
- Under the contingency condition, all DFRs can help to improve frequency stability of the practical system as the frequency controlled disturbance reserve.
DFR II is faster in disconnecting the loads therefore more effective for frequency control in response to the contingency, while DFR I and its variant only start to disconnect the loads at pre-set frequency threshold and have similar performance in the disconnection procedure. The lowest frequency after the contingency is improved from 49.867 Hz for the case without DFR, to 49.88 Hz and 49.92 Hz for cases with DFR II (concentrated and distributed) and DFR I (and its variant) respectively.

- When system frequency recovers from the contingency, the demand of DFR II will start to come back right away. The demand of DFR I and its variant will not be back until the frequency recover above the reconnection set point and after pre-set time delays. The DFR I can have a larger ‘return energy’ (compared to other DFRs), therefore causing bigger oscillations in frequency as also found in Section 6.2

- The installation location of DFR loads seems having little impacts on the simulation results with respect to frequency control under normal or contingency conditions. The installation location of DFR loads certainly has impacts on power flows in the system.

- For contingency events in a practical power system, the DFR control logics will not turn off electric appliances infinitely, therefore limiting the discomforts to customers. In stead, they will coordinate the operation cycles of the appliances to improve frequency stability.

**Third case - Bornholm power system integrated with and without DFR in islanded operation mode**

In the third case, the DFR’s performance as normal and disturbance reserves, when integrated with a practical small power system in islanded operation mode, is to be investigated. A preliminary model of Bornholm power system is used (see in Figure 24), which is an island in Eastern Denmark [14] [15]. Major technical information of the model is given below. This model is still preliminary and to be improved in the future. The Bornholm system has a peak load capacity of about 55 MW and a base load of 25 MW. The peak demands of the total system and electric heating appear simultaneously during winter time, and the electric heating occupies approximately 10% of the total demand [14].

<table>
<thead>
<tr>
<th>Table 7 Major technical information of Bornholm power system</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsystem</strong></td>
</tr>
<tr>
<td>Substation/Busbar</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td>System demand</td>
</tr>
</tbody>
</table>
considered for both real (P) and reactive power (Q) of these loads. In addition, 6 induction generators are included (at 10 kV) to represent the wind turbines at Bornholm.

**Generators**

Five generators are modelled. Controllers for secondary and primary mover control have been included for most of these generators.

![Figure 24 Bornholm power system model](image)

The electric heating loads at Bornholm are distributed at several places. Since the installation location has small impacts on DFR performance as demonstrated in Section 6.3, only one DFR heater model i.e. 500 individual units, is built and connected at that same bus in the Bornholm model. A scaling factor of 2.5 is applied to the model, so that the total installation capacity of heaters is about 5 MW. This is about 10% of total system demand (installation capacity), i.e. the system has:

- **Constant load**: 45 MW and 37.5 Mvar, distributed unevenly among buses
- **Electric heating**: 5 MW (installation capacity) at bus NOR010B_SFIK (purple circle in Figure 24), with a typical load of 1.7 MW in the simulations.
- **Total installation capacity of system demand is**: constant load + electric heating = 50 MW
Simulation cases for a generation contingency and normal operation with wind power will be carried out. The heaters will be installed with and without DFR functions in these simulations, which will have different impacts on the results. To study this, we define the percentage of the installed DFR heaters capacity versus the total system demand (installation capacity) as the capacity penetration level of DFR heaters, i.e.:

\[
\text{DFR penetration level} = \frac{P_{\text{DFR heater}}}{P_{\text{total system}}} \times 100\%.
\]

(Note: \(P_{\text{total system}} = P_{\text{constant load}} + P_{\text{DFR heater}} + P_{\text{non-DFR heater}} = 50 \text{ MW}, \)
\(P_{\text{DFR heater}} + P_{\text{non-DFR heater}} = 5 \text{ MW}, \) and \(P_{\text{constant load}} = 45 \text{ MW}\))

Consequently, the variation of the amount of the DFR heaters can be quantified by this index. Totally, six DFR penetration levels have been considered at 0%, 1.5%, 3%, 5%, 7.5%, and 10% respectively. 0% indicates all heaters are without DFR functions, and 10% indicate all heaters are installed with DFR function.

The defined penetration level may not reflect the actual demand from DFR heaters in simulations. This is because they may not be on all the time, and consequently their consumption power is changing. Therefore, instead of using the actual power, the installed capacity is used in quantifying the amount of DFR heaters in order to achieve a fixed number irrespective of the simulation time. The actual power of DFR heaters should be smaller than the levels defined. The levels actually indicate the maximum demand that can be available from DFR heaters.

A generator event (2 MW reduction in output) considering different capacity penetration levels of DFR

A generator contingency, i.e. a 2 MW reduction of output power of the generator at bus “s_VÆRDSLBC”, will be simulated to examine DFR’s performance as disturbance reserve. The contingency will be simulated at \(t=1500\text{s}\) with a total simulation time of 3000s. Different capacity penetration levels of DFR heaters have been considered in the simulations, and the heaters are the only fluctuating elements in the system.

The simulated system frequency and demand of the heater model, including cases of different capacity penetration levels of DFRs, have been presented in Figures 25 to 27. Because the system model is still preliminary, frequency oscillations below than 49.90 Hz appear in the beginning of simulations, which can cause DFR I_a and I_b functions to be activated. If so, the heaters with DFR I_a and I_b will be oscillating continuously which will affect their performance for the contingency later on, given
the limited simulation time of 3000s. Therefore, the function of DFR I_a and I_b have been disabled during the initial 5 s. This is just a trade-off due to the limitation of the system model. The system model will certainly be improved in the future. Since DFR II has excellent capability of self regulation as observed in previous case studies, the initial oscillation will cause little impacts to its contingency performance later on. Therefore DFR II function is not disabled during the initial simulation period.

In addition, the lowest frequency versus corresponding observation time at different DFR capacity penetration levels in all simulation are presented in Figure 28.
Figure 25 System frequency (upper plot) and the power (lower plot) of the DFR Ib model in the E60
Figure 26: System frequency (upper plot) and the power (lower plot) of the DFR I model in the contingency case.

NOR010\NOR010B_SFIK: Frequency in Hz with 0% DFR
NOR010\NOR010B_SFIK: Frequency in Hz with 1.5% DFR
NOR010\NOR010B_SFIK: Frequency in Hz with 3% DFR
NOR010\NOR010B_SFIK: Frequency in Hz with 5% DFR
NOR010\NOR010B_SFIK: Frequency in Hz with 7.5% DFR
NOR010\NOR010B_SFIK: Frequency in Hz with 10% DFR

DFRLoad: Active power in MW with 0% DFR
DFRLoad: Active power in MW with 1.5% DFR
DFRLoad: Active power in MW with 3% DFR
DFRLoad: Active power in MW with 5% DFR
DFRLoad: Active power in MW with 7.5% DFR
DFRLoad: Active power in MW with 10% DFR

DIgSIL
Figure 27 System frequency (upper plot) and the power (lower plot) of the DFR II model in the contingency case.
From Figures 25-28 it has been observed

- DFR Ia and Ib generate similar simulation results except for the reconnection as already observed in sections 6.2-3. At various capacity penetration levels other than 0%, DFR II generally has the best performance in terms of the lowest frequency after the event. (All DFRs should generate the same result at 0% penetration though little difference caused by random disturbance in the model).

- As the penetration level increases, the lowest frequency caused by the contingency increases for all types of DFRs, and the observation time becomes earlier as well. E.g. with 0% DFR, the lowest frequency is about 49.75 Hz at t=1503s; with 10% DFR, the lowest frequencies are improved to 49.84 Hz at t=1501.3 s for DFR Ia and Ib, and 49.90 Hz at t=1501s for DFR II.

Integration with fluctuating wind generation under normal condition considering different capacity penetration levels of DFR II loads

The Bornholm power system has a total 30 MW installation capacity of wind generation. Currently, the wind generation has to be largely curtailed to maintain frequency stability during islanded operation. In this case study, fluctuating wind generation based on actual measurement data and DFR II load will be integrated into the
Bornholm system model to simulate the normal islanded operation, in order to evaluate DFR’s capability as normal reserve.

For simplicity, one 2 MW wind turbine is integrated at bus NOR010B_SFIK, i.e. the bus where DFRII locates. The wind turbine model consists of one fixed speed induction generator (FSIG), and modules of pitch control, aero dynamics and a simplified two mass turbine shaft model [21] [22]. The parameters of the turbine model are based on those in the literatures [32, 33]. The wind turbine model is preliminary and has not been validated. More details about the wind turbine model can be found in the Appendix B.

In this case study, the capacity penetration levels from 0% to 10% of DFR II load is considered for all simulations. Actual wind speed data is used as the input to the wind turbine model. Due to the unavailability of wind data of Bornholm, the data used is wind speed measurement at Lammeefjorden, Denmark from 16:00~17:00pm, July 24 1987, with a resolution of 1/8 seconds per sample. Since the objective of this case study is to introduce fluctuations in normal operation, such a replacement does not lose its generalities in this context. The first 1000s of the wind speed data is used in the simulations. The wind speed during this period ranges from about 3 to 9 m/s. The wind turbine is modeled with a small cut in speed (< 3 m/s) to be able to generate electricity during the simulation. The cut off speed for wind turbines is typically 25 m/s which is far above the wind speed range in consideration. Figure 29 shows the wind speed in m/s and the wind turbine’s real and reactive generations in MW/Mvar. It can be seen that the wind speed is rather chaotic, resulting in fluctuations in real and reactive generation of the wind turbine. In real life the distance between the wind turbines would smooth out the delivered effect. However, this smoothing effect is not studied here. The mean, min, max and standard deviation for the results in Figure 29 have been calculated and presented in Table 8.

Figure 30 presents simulated system frequency and the output power of the DFR II model with different penetration levels. The average, max and standard deviation of frequency errors and the lowest observed frequency in figure 30 have been presented in Figure 31.
Figure 29 Wind speed, real and reactive generations of the wind turbine model

Table 8 Statistics of wind speed, and resultant real and reactive generations of the wind turbine during the simulation

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed m/s</td>
<td>3.04</td>
<td>9.8373</td>
<td>6.0266</td>
<td>1.0708</td>
</tr>
<tr>
<td>P MW</td>
<td>0.001</td>
<td>0.5531</td>
<td>0.1789</td>
<td>0.0952</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>Mvar</td>
<td>0.3815</td>
<td>0.5929</td>
</tr>
</tbody>
</table>
Figure 30 System frequency (upper plot) and the power (lower plot) of the DFR II model in the normal operation with single wind turbine.
From Figures 29-31, it is observed that:

- Due to the fluctuating wind, the generated wind power fluctuates in the simulation period, resulting in fluctuations in system frequency for all cases.

- With higher penetration of DFR load, the simulated frequency will have smaller errors of average, maximum and standard deviation. From 0% to 10% penetration level, max frequency error drops from about 0.2 to 0.104 Hz, the average error drops from about 0.07 to 0.05 Hz, and the standard deviation of frequency error drops from about 0.024 to 0.018 Hz. The observed lowest frequency increases from about 49.80 Hz up to about 49.90 Hz as the penetration level increases from 0% to 10%. Accordingly, the fluctuations in the output power of the DFR model are observed to increase as penetration levels increases.

Based on the above, conclusion of this section can be made.

**Conclusion from this section**

In the section, the Bornholm system have been simulated for a generator contingency case and normal operation wind cases, considering different capacity penetration levels of DFR load. Based on the simulation results, several conclusions can be drawn as follows,

- DFR is stable when integrated with a practical small power system in islanded operation

- Under the contingency condition, all types of DFRs can help to stabilize system frequency as disturbance reserve, and the performance of DFR, with respect the
observed lowest frequency caused by a 2 MW generation outage, seems proportional to the penetration level. The frequency dip is reduced from about 49.75 Hz to 49.90 Hz with 0% and 10% penetration of DFR II, and from about 49.75 Hz to 49.84 Hz with 0% and 10% penetration of DFR I (and the variant). Generally, DFR I and its variant have little difference in performance, and DFR II outperforms other types for the contingency.

- Under normal operation with wind generation (of various capacities), DFR II can help to improve the frequency quality with respect to frequency error as normal reserve. The performance of DFR II as normal reserve seems proportional to its penetration level, since the mean, max and standard deviation of frequency error decrease proportional to the penetration level.

### 2.7 Conclusion and Future work

This report studies modeling and simulation of demand as frequency controlled reserve. The theoretic foundation of using DFR for power system frequency control has been studied. Three types of DFR models have been developed using DIgSILENT Power Factory. Comparison of different DFR models and optimal design of model parameters with respect to frequency control objective have been discussed. Simulations of DFR integrated with various practical power systems have been carried out, which indicates the DFR is a technically feasible solution for frequency control, especially for the future power system where high penetration of fluctuating renewable generation e.g. wind generation is foreseen. Specific conclusions can be drawn as follows,

- The developed DFR models are stable when integrated with practical power systems of large or small size
- Simulations of contingency conditions show that all types of DFRs can help to stabilize frequency as frequency controlled disturbance reserve. The performance of DFRs with respect to the lowest frequency caused by the contingency seems proportional to its penetration level, i.e. the more DFR load is, the earlier and higher the lowest frequency will be observed after the contingency.
- DFR with external control can have negative consequences for the system. If the full capacity of electric heating is set on when reconnected (type 1b), over swing or even instability can occur. The full capacity of electric heating is often much larger than the actual consumption – depending on the outdoor temperature.
- Simulations of normal conditions with fluctuating wind generation show that the DFR II model can help to improve frequency quality as frequency controlled normal reserve. The performance of DFR with respect to the frequency error seems proportional to its penetration level, i.e. the more DFR load is, the smaller the average and maximum frequency errors will be
• Different allocation of DFR loads in a power system seems having little impacts on its performance of frequency control, though it will affect power flows in the system

Further research concerning dynamical modeling and simulation of DFR can be carried out to

• Further develop DFR models to e.g. design new control logics such as multiple coefficients for DFR II etc, include dynamic characteristics such as voltage and frequency dependences, and consider demands for other than electric heating for DFR such as air conditioner, refrigerators and freezers etc
• Improve the power systems models and carry out simulation studies
• Evaluate the impacts of DFR function to the operations of loads through dynamic simulations
• Investigate DFR for intentional islanding operation of distribution networks

In other work packages of the project, monitoring methods and business model for implementing DFR will be investigated. Other demand side technology and the interplay with the DFR can also be investigated, e.g. the interplay between DFR and the price responsive demand. The demand as voltage controlled reserve (DVR) is another demand side technology of high potential and should be studied as well. Use of demand to prevent voltage collapse on the transmission level may require communication and coordination with other voltage control techniques. E.g. during the blackout of Eastern Denmark and South Sweden in 2003, the oscillation faded away after 90s of the initial bus bar fault and the system started to stabilize. However, the demand in the impacted area at the same time ‘gradually recovered from the initial reduction following the voltage drop by action of the numerous feeder transformer tap-changers’ [31]. This resulted in continuously lowered voltage in the 400 KV transmission level, and further developed into voltage collapse in a section of the grid south-west of the area around the capital city Stockholm. Communication could be unnecessary if use of demand is for general voltage quality improvement in low voltage distribution network. Despite the communication requirement, it is possible to combine DFR and DVR technologies for certain demands, since most demands e.g. compressor type demands like air conditioner and refrigerators consume both real and reactive power, Furthermore, the demand will play an important role in the control architecture for the future power system, where a high share of fluctuating renewable energy is foreseen [23] [24]. In such architecture, the demand side technology including both DFR and DVR should be included and coordinate with other techniques such as frequency control of wind turbines [25] to enable flexible operations like intentional islanding etc [26].
2.8 References in this chapter


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2.9 Appendices

Understanding the DFR - simulation of an OMIB system with on-off active load control for damping electro-mechanical oscillation

Figure A1 shows the MATLAB Simulink model of the OMIB system in Section 2. Major parameters of the system are given in Table A1.
Figure A1 MATLAB/Simulink model of the OMIB system with on-off control of an active load

Table A1 parameters of the OMIB system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1'$</td>
<td>1.281 p.u.</td>
</tr>
<tr>
<td>$H$</td>
<td>4 s</td>
</tr>
<tr>
<td>$x_d'$</td>
<td>0.35 p.u.</td>
</tr>
<tr>
<td>$x_e$</td>
<td>0.4 p.u.</td>
</tr>
<tr>
<td>$P_{load}$</td>
<td>0.1 p.u.</td>
</tr>
<tr>
<td>$P_{m1}$</td>
<td>1.1 p.u.</td>
</tr>
<tr>
<td>$\delta$ (initial)</td>
<td>0.5255 rads</td>
</tr>
<tr>
<td>Damp</td>
<td>0</td>
</tr>
</tbody>
</table>

A three phase short circuit fault at the Generator 1 terminal bus is simulated at t=0s as a disturbance to the system. The fault is of very short duration i.e. 0.06 s, and the total simulation period starts from -1 to 3 seconds. Two cases have been considered:

- Case 1: $P_{load}$ without on-off control.
- Case 2: $P_{load}$ with on-off control, i.e. $P_{load}$ will be turned on if G1’s rotor speed $\omega \geq 1$, will be turned off if $\omega < 1$. No time delay is involved in the switching.

For Case 1, since no damping in the system, the disturbance will cause the G1’ rotor angle and speed to oscillate around the initial state. For Case 2, since the on-off control will change the power angle curve of the system as discussed in Section 2, and the oscillations of G1’ rotor angle and speed will be then effective damped. The simulation results in Figure A2 verify the analyses.
**Figure A2** Simulation results of the OMIB with/out on-off control of an active load.

Oscillatory trajectory of G1 in \((t, \delta, \Delta \omega)\) space in Case 1

Damped (by on-off control \(P_{\text{load}}\)) trajectory of G1 in \((t, \delta, \Delta \omega)\) space in Case 2

Projection of the left into \((\delta, \Delta \omega)\) space
The wind turbine model

The wind turbine in Section 6 is a fixed speed induction generator type. It consists of modules of pitch control, area dynamics, shaft, asynchronous machine and wind speed measurement data. Voltage control/compensation and soft starter for the wind turbine is not considered in the modeling since it is not the focus of this project. The composite frame of the wind turbine model in DiGITALent is shown in Figure B1. Figures B2–3 shows the modules included.

Figure B1 composite model of the wind turbine: speed denotes the generator rotor speed, pt generator shaft power, vw wind speed data, Pwind is the aerodynamic power develop at main shaft of wind turbine, beta is the blade angle.

Figure B2 Simplified two mass wind turbine shaft model: speed_gen denotes the generator rotor speed, Pwind is the aerodynamic power develop at main shaft of wind turbine, pt generator shaft power, rotor is rotor angular speed.
Pitch Angle Control:

Figure B3 Pitch angle control model: speed denotes the generator speed, \( \omega \), \( \Phi \) generator shaft power, rotor is rotor angular speed

The aero dynamics of the wind turbine is modeled using the equation below

\[
P_{\text{wind}} = C_p(\lambda, \beta) \cdot \frac{1}{2} \rho v^3
\]

where \( C_p(\lambda, \beta) \) is the power coefficient of the wind turbine and is non-linear depending on wind speed \( v \), mechanical speed \( \omega \), and blade angle \( \beta \). \( \lambda = \frac{\omega R}{V_w} \) is the tip-speed ratio where \( R \) is radius of wind turbine blades. \( A \) is the turbine swept area.

In the developed model, the function \( C_p(\lambda, \beta) = f(\lambda, \beta) \) is realized using a spline approximation of a series of \( C_p - \lambda \) characteristics. Figure B4 shows the formulated \( C_p(\lambda, \beta) \) characteristics for different pitch angles. Table B1 gives the major parameters of the wind turbine model.
Figure B4 The $C_p(\lambda, \beta)$ and mechanical power-wind speed characteristics of the 2 MW wind turbine model

Table B 1 Major parameters of the wind turbine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power MW</td>
<td>2</td>
</tr>
<tr>
<td>Wind turbine rotor inertia $10^6$ kg m²</td>
<td>7</td>
</tr>
<tr>
<td>Generator rotor inertia kg m²</td>
<td>120</td>
</tr>
<tr>
<td>Shaft stiffness MNm/rad</td>
<td>145</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>95</td>
</tr>
<tr>
<td>Turbine radius m</td>
<td>33</td>
</tr>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
</tr>
</tbody>
</table>
3

MONITORING FREQUENCY CONTROLLED DEMAND AS RESERVE

3.1 Abstract

The electricity system needs reserves to offset sudden loss of generation or transmission capacity. The amount of available reserves must be well known so system behaviour is predictable. Traditionally, these reserves are delivered by large scale power plants or DC-transmission lines. However, as demonstrated in this research project [1, 2], as well as in other projects [8], small scale demand can act as frequency controlled reserves – and can be superior e.g. in reaction time. Frequency controlled demand can be utilised for normal operation (49.9 – 50.1 Hz) as well as and in relation to disturbances (outside the normal frequency interval).

Demand as frequency controlled reserve (DFR) comes in different types. The basic type of DFR is autonomous, e.g. with frequency control of electric heating or a household appliance without any communication to the control system. A reliable and accurate monitoring of the available reserves of this type is crucial for the transmission system operator (TSO). Reliable monitoring of autonomous DFR can be used to adjust the amount of traditional reserves, like the controllable reserves from power plants and DC-lines. In this way the required reserves can be maintained within acceptable limits.

The approach to monitoring reserves must be developed to fit with a large number of autonomous units. The use of traditional real time metering methods is highly expensive and is like using a sledgehammer to crack a nut.

This chapter describes and demonstrates secure ways to monitor large number of small demands by using statistical methods.
3.2 Factors influencing the design of monitoring

The design on a monitoring plan can be developed based on the requirements for accuracy in the results and the degree of variability of the issue in focus. If little variability exists a small sample can be used. With just a few observations, the overall result is known. If, on the other hand, the outcome is very unpredictable – a total measurement must be used, i.e. measurements must be applied to all units.

Monitoring demand in the day-ahead market

In the day-ahead market, traders buy electricity for next day’s demand based on historical values of the electricity demand. The newest metered values are typically days old. By using such data combined with time series, e.g. with years values with information about the calendar (weekdays, weekend, and holidays) and with temperature it can be used to predict tomorrow’s aggregated electricity demand with high precision, e.g. based on a regression analysis of hourly values of electricity demand with calendar and temperature as explanatory variables can yield high degree of goodness of fit (with $R^2$ above 90% - $R^2$ denotes the percentage of variation in the dependent variable accounted for the independent predictor variables).

When access to metered data is available with only short delay (e.g. less than a day) autoregressive methods (autoregressive integrated moving average, ARIMA) can be considered as a good methodology to achieve satisfactory results.

Predicting the electric demand for a single house with electric heating can be difficult, while estimating the demand for a larger population is an easier task. The impact of aggregating just a few houses is significant.

Importance of the number of units

Statistical methods are best suited for large numbers of units. With 20 or more units the aggregated results start to behave in accordance with the law of large numbers. The individual and random results start to smooth out.

Probability of successful start

The need for online-measurements is dependent on the number of unit to be controlled. This can be illustrated by a simple calculation. One critical issue is whether the ordered reserves actual start. Figure 1 shows the results of a number of calculations of the start problem by use of binominal distribution. The assumption is that the probability of a successful start is 90% per unit.

Figure 1 depicts three different test cases for 1, 3 and 1000 units, respectively. In all cases the total volume is 100 MW. With 1,000 small 0.1 MW units the expected outcome is very predictable. The successful starts correspond to 90 MW +/- 2 MW in 97% of all cases – a very predictable outcome.
With fewer units (here illustrated with 3 units and 1 unit), the variation increases and the need for knowing the result is augmented.

![Production (MW) vs. Fraction of all experiments with the indicated production or higher](image)

*Figure 1. The available production for units each with a 90% probability of successful start. The three lines indicate: 1, 3 or 1,000 units. With 1 unit the expected production is 100 MW in 90% of the cases and 0 MW in the last 10%. With 1,000 units the expected production is 90 MW +/- 2 MW in 97% of all cases.*

In this calculation, it is assumed to have the same starting probability for all the cases. This may not be the best assumption in real life. However, the variation will inevitably be less with many units. Statistical methods may be relevant in relation to many units – just as with the electric demand.

**Aggregation of units**

While it is impossible to predict the hourly electricity demand for a single household (see figure 2.a.), it is easy to predict the demand for a large number of houses. In figure 2.b. it is illustrated that a sample of 10 is too small to give clear picture of the total population. In figure 2.c it can be seen that a sample of 100 houses gives a stable outcome. The most important parameter for determining the appropriate sample size is the variation in the demand (figure 2.a), while the size of the total population has less importance.

With 100 houses a statistical model can be used to find the structural impact of time of the day and temperature. This is shown in table 2 and in appendix 1.
Total population: 249 single family houses with electric heating. Data from 15 December 2007. Average temperature: 5.3°C. Data is from the control group in a demand response experiment at SydEnergi and SEAS/NVE.

Figure 2.a. Hourly electricity demand at 24 individual houses

Figure 2.b. Average consumption based on a five random samples of 10 houses.

Figure 2.c. Average consumption based on a five random samples of 100 houses.

Requirements for monitoring of reserves

Monitoring of activated reserves serve several purposes:

- Verification: To document that the ordered energy is delivered. Both energy and activation time has to be fulfilled. For regulating power the ordered power must be delivered within 15 minutes notice. Automatic frequency controlled disturbance reserves must be activated 50% within 5 sec. and 100% within 30 sec. To be able to document activation, the time solution must accordingly short, e.g. minutes for regulating power and seconds for disturbance reserves.

- Billing: For disturbance reserves the reservation costs are the most important. For regulating power activation price is also important, and this is managed though the hourly measurements per balance responsible.

The current practise with online measurements is well suited to large units. For large number of small units a statistical approach can be used, and can provide the same level of confidence and online measurements.

The current practice of requiring online measurement is not based on a formulated quality requirement. To develop the appropriate monitoring strategy the basic requirements could be formulated in the form e.g. “when 25 MW regulating power is
ordered, the value should be realized +/- 10% with 90% probability”. With such a requirement a monitoring strategy can be developed. It can be tested if a statistical method based on historical data can fulfil the requirements, like the method the traders use.

If the required level of accuracy cannot be achieved by the statistical method, measurement of a sample of the total population can be included, e.g. a 10% sample with real time or measurements a few hours old would increase the accuracy.

<table>
<thead>
<tr>
<th>Number of units</th>
<th>Accuracy</th>
<th>Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Few units</td>
<td></td>
<td>Online measurements</td>
</tr>
<tr>
<td>Many units</td>
<td>Medium accuracy</td>
<td>Statistical methods on historical values</td>
</tr>
<tr>
<td>Many units</td>
<td>High accuracy</td>
<td>Statistical methods combined with online measurement of a sample</td>
</tr>
</tbody>
</table>

Table 1. Three cases for monitoring

In the following a few examples for predicting the demand are given.

**Examples of monitoring demand**

In some cases prediction of DFR can be sufficiently accurate. Prediction can be based on historical values for a sample or a total population. If data are analysed in a model and relevant parameters, e.g. outdoor temperature, is known for the next day – then a prediction can be done. This approach is well known for the TSO in relation to electricity demand and generation from small CHPs and from wind power.

The accuracy of predicting demand is illustrated here. In appendix 1 three data sets are presented and analysed using regression analyses. Results are shown in table 2.
Table 2. Results from four regression analyses.

<table>
<thead>
<tr>
<th></th>
<th>EFFLOCOM-model 1</th>
<th>EFFLOCOM-model 2</th>
<th>Elforbrugs-panelerne</th>
<th>Bornholm Residual demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of houses</td>
<td>22</td>
<td>22</td>
<td>~100</td>
<td>~28,000</td>
</tr>
<tr>
<td>Type of demand</td>
<td>Electricity used for heating and controlled with price signal</td>
<td>All demand in single family houses with electric heating</td>
<td>All demand in end-users without interval meter</td>
<td></td>
</tr>
<tr>
<td>Number of parameters in model</td>
<td>4</td>
<td>23</td>
<td>79</td>
<td>79</td>
</tr>
<tr>
<td>N (number of hourly values)</td>
<td>12,334</td>
<td>12,334</td>
<td>17,540</td>
<td>11,374</td>
</tr>
<tr>
<td>R² adjusted</td>
<td>82.5%</td>
<td>92.8%</td>
<td>94.1%</td>
<td>94.2%</td>
</tr>
<tr>
<td>Active power average</td>
<td>1.455 kW</td>
<td>1.455 kW</td>
<td>1.453 kW</td>
<td>18.859 MW</td>
</tr>
<tr>
<td>Percentile of residuals, P5%</td>
<td>-0.60 kW</td>
<td>-0.41 kW</td>
<td>-0.27 kW</td>
<td>-1.978 MW</td>
</tr>
<tr>
<td>P10%</td>
<td>-0.41 kW</td>
<td>-0.30 kW</td>
<td>-0.20 kW</td>
<td>-1.431 MW</td>
</tr>
<tr>
<td>P90%</td>
<td>0.40 kW</td>
<td>0.32 kW</td>
<td>0.21 kW</td>
<td>1.526 MW</td>
</tr>
<tr>
<td>P95%</td>
<td>0.54 kW</td>
<td>0.42 kW</td>
<td>0.28 kW</td>
<td>2.030 MW</td>
</tr>
<tr>
<td>90% interval *</td>
<td>1.5 kW +/-0.6 kW (40%)</td>
<td>1.5 kW +/-0.4 kW (26%)</td>
<td>1.5 kW +/-0.3 kW (20%)</td>
<td>18.9 MW +/-2.0 MW (11%)</td>
</tr>
<tr>
<td>80% interval*</td>
<td>1.5 kW +/-0.4 kW (26%)</td>
<td>1.5 kW +/-0.3 kW (20%)</td>
<td>1.5 kW +/-0.2 kW (13%)</td>
<td>18.9 MW +/-1.5 MW (8%)</td>
</tr>
</tbody>
</table>

If the demand is well known with a +/- 15% or better with 90% probability, then the Bornholm model can deliver this – only based on a statistical analysis.

The intervals presented in table 2 are found for the same data that the regression analysis uses. In practise one would estimate the regression on historical data and extrapolate the result to the future. This would increase the uncertainty intervals.

The above examples are based on data with hourly values. Intra hour variation in the demand from aggregated values for a large number of electric heating or household appliances are expected to be limited. This can be illustrated by the result found in the appendix: That electric heating is only 24% lower in night compared to day time. Other types of DFR may show a higher intra hour variation, e.g. washing machines or tumble dryers.

3.3 A sketch of a monitoring plan for DFR in Denmark

In Denmark more than 110,000 single family houses are heated with electricity. Let us assume that 10% of these have a DFR controller for the electric heating. The task is now to design a monitoring system, which enables the TSO to know the amount of DFR reserves at any given hour.

From the analysis of the Elforbrugspaneler it is known (see appendix) that for each degree the outdoor temperature is below 17°C the electricity demand is increasing 0.54 kW per house, or 0.6 MW/degree day for 11,000 houses. We also know the daily variation. Information can be used to calculate the actual level of DFR. At 0°C the
demand would be 10 MW, and at -10°C 16 MW. This would have accuracy in the order of +/- 20%. These values are for a standard house using 12,600 kWh/year.

The model could be improved in several ways. E.g. adjustment could be made to reflect the actual consumption to the participating houses. Yearly readings of total electricity consumption in the participating house would improve the results. This could also allow for a selection of houses with above average consumption – to reduce the investment cost.

Interval meters or even real time meters could further improve the accuracy. A sample of e.g. 50-100 houses could be used to create an updated and credible picture of the available reserves. One option could be to use the sample that is already used for the Elfbrugspaneler. If the extra meters was installed directly for the electric heating (and not other types of electricity use) the accuracy would also be increased.

3.4 References in this chapter

(1) M. Togeby, Z. Xu, and J. Østergaard, ‘DFR project work package one report- - Potentials and perspectives’, draft, November 2006

(2) Z. Xu, J. Østergaard, M. Togeby, ‘DFR project work package two report- - Dynamic simulation of chosen concepts’, draft, October, 2007

(3) M. Togeby, Z. Xu, and J. Østergaard, ‘DFR project work package three report- - Monitoring frequency controlled demand as reserve’, draft, January 2008


3.5 Appendix Modelling demand response in 22 houses with electric heating

Demand response has been tested for two winters in 22 single family houses with electric heating – all equipped with an automatic system for price response (see Kofod and Togeby, 2005). During each winter period the households were exposed to 100 hours with high prices, grouped as 1 hour, 2 or 3 hours with high prices in a row.

The electricity demand can be described in the following simple equation, EFFLOCOM- model 1:

\[
\text{Consumption} = \alpha_1 + (\alpha_2 - \alpha_3 \times \text{Interrupt} + \alpha_4 \times \text{Return} - \alpha_5 \times \text{Night}) \times \text{DD}
\]

\[
\text{Consumption} = 0.036 + (0.148 - 0.140 \times \text{Interrupt} + 0.061 \times \text{Return} - 0.035 \times \text{Night}) \times \text{DD}
\]

Where:
- Consumption is the average consumption per house per hour in kW
- Interrupt is 1 at times of interruption (high price) and 0 the rest of the time
- Return is a description of the return load on the hours after an interruption. The profile for the return energy has by experiment been found to be: 0.75, 0.15, 0.05, 0.025, and 0.025 for the five hours following an interruption.
- Night is 1 in the day period 00-06 hours and 0 the rest of the time
- DD is degree days defined as the average of the degree days for the last 24, 28 and 72 hours. Degree days are defined as: 17 - the average daily temperature (°C).

For day time hours without interruption (Interrupt=0, Return=0, Night=0) the equation can be simplified to:

\[
\text{Consumption} = 0.036 + 0.148 \times \text{DD}
\]

\(\alpha_2 = 0.148\) kW/degree day is the extra demand per each reduced 1°C the temperature is reduced.

The coefficients are found by a linear regression. This five variable equation can explain \((R^2) 82.5\%\) of the variation in the demand. Data are hourly values for two winters (1st November 2003 to 1st April 2005).
With a larger sample (more houses) an even higher $R^2$ can be expected. A more detailed description of the time of day and time of year could also increase $R^2$. This is tested in EFFLOCOM-model 2:

$$\text{Consumption} = \alpha_1 + \beta_1 \cdot F(\text{year}, 5) + (\alpha_2 + \beta_2 \cdot F(\text{day}, 5) - \alpha_3 \cdot \text{Interrupt} + \alpha_4 \cdot \text{Return}) \cdot DD$$

$$\text{Consumption} = \alpha_1 + \beta_1 \cdot F(\text{year}, 5) + (\alpha_2 + \beta_2 \cdot F(\text{day}, 5) - 0.148 \cdot \text{Interrupt} + 0.058 \cdot \text{Return}) \cdot DD$$

Where $F(X,Y)$ is a 2*Y Fourier series with base X and with Y sinus curves and Y cosines curves. $\beta_i$ is a vector with 2*Y values. E.g. for the seasonal part five sine and five cosine each with the period 1 year, ½ year, 1/3 year, ¼ year and 1/5 year. Similar for the day, where the base period is 1 day.

### Figure 1.1

**Figure 1.1. Dependency of temperature ($\text{kW per degree day}$) vs. time of day.$\alpha_2 + \beta_2 \cdot F(\text{day}, 5) \cdot DD$ in model 2**
Figure 1.2. Variation of non-temperature depended part of electricity demand vs. time of year, e.g. for hot water. $\alpha_1 + \beta_1 F(\text{year}, 5)$ in model 2.

Results from the two models are presented in table 1, together with two other models covering a large number for households.

3.6 Modelling electric heating and residual demand

The “Elforbrugspanelerne” is a data base with electricity measurement with hourly values covering a number of different segments. Each segment is based on a representative sample. Data has a panel structure, i.e. the same units are included over time. Here is used the end-user segment “single family houses with electric heating” for two years, corresponding to 2003 and 2004, respectively. Data from Elforbrugspanelerne is original normalised, so the sum of all values for a year is equal to one. Here the values have been multiplied to get the same average as for EFFLOCOM.

Furthermore, the so-called residual demand for Bornholm is analysed. The residual demand is the total demand minus the measured demand with interval meters. So then, this includes all demand without interval meters. Only consumers with a yearly consumption above 100,000 kWh have an interval meter. The residual demand is dominated by households and small businesses.

Seasonal and daily variation is modelled by 10 coefficients to describe the seasonal variation and 60 coefficients to describe the daily variation (10*2*3: 3 day types, and two seasons: summer and winter). Each coefficient is related to a sine or cosine curve. E.g. for the seasonal part five sine and five cosine each with the period 1 year, $\frac{1}{2}$ year, $\frac{1}{3}$ year, $\frac{1}{4}$ year and $\frac{1}{5}$ year. This model approach is called Fourier curves.

Furthermore, degree days as well as cooling days are included, as well as an individual level for
Mondays, Fridays, Saturdays and Sundays. This is also the way summer holidays and days between holidays are modelled. In total 79 coefficients are used to model the hourly demand.
4

STRATEGY AND PRACTICAL IMPLEMENTATION

4.1 Abstract
Due to their construction and service, many electric devices can be disconnected from their main power supply for a short period of time without disturbing their functionality, or the end user comfort. Some examples of these devices are related to thermal comfort such as the direct electric heating, heat pumps, air conditioning, circulation pumps, refrigeration and freezers. Such demand can be controlled to act as reserves, e.g. automatic frequency controlled normal reserves or disturbance reserves. It is practiced e.g. in Finland to use industrial loads as automatic frequency controlled disturbance reserves and in Norway and Finland to use industrial loads as manual reserves (regulating power). However, due to development in electronic control, also small scale demand can be used as reserves.

Technical aspects of using demand as frequency controlled reserves (DFR) have already been described (see chapter 1-3 in this report). This chapter reports on the practical and economical issues regarding DFR, including potential synergy with traditional demand response, analysis of potential for DFR and practical implementation.

4.2 Synergy with demand response
Demand as frequency controlled reserves can be implemented autonomous. This means that no communication links are required. This can be economically attractive in relation to small domestic load, e.g. freezers, refrigeration, and pumps. Such loads are typically in the order of 10-100 W (yearly average). Even few extra costs can be too expensive – and communication may not be needed for these appliances.

In other cases communication can be included. This can be relevant in relation to larger loads where the extra costs are less a burden. This is a typical matter for industrial loads where the active power consumption is from 100 kW to 10 MW. There are some other electric devices which already possess communication systems or which can take advantage of this technology at low cost. In fact, heating systems are close in relation to
these aspects, where the control system already exists for comfort and remote control can be enable (e.g. in relation to summer cottages). Systems for entertainment and home automation are emerging on the market and may include communication and possibilities for control of demand and for monitoring (e.g. Electronic Housekeeper, ehweb.electronichousekeeper.com or Innovus, www.innovus.dk).

Furthermore, a communication system can be established to perform demand response (price controlled demand). Many of the same end uses relevant for demand response can also be used for DFR, e.g. electric heating or heat pumps (1 – 5 kW).

If communication system exists it can also be applied in relation to DFR. Typically the communication schemes are used to control the set-point and other parameters, and are not necessarily applied for the connection/disconnection of the electric device. Local measurement of the frequency makes instantaneous reaction possible, e.g. with delays below 0.5 sec.

Communication system can also be utilised for monitoring and for payment purposes. Monitoring of DFR can be used for a sample as a basis to calculate the available capacity. E.g. in relation to electric heating it can be relevant due to daily and seasonal variation in the electric consumption.

If the user can decide when to activate or deactivate the DFR function, the monitoring becomes an important function.

On the investment side, communication schemes can play an important role if the DFR and demand response from the same appliance is active. However, on the other hand it may make the monitoring aspect more challenging when DFR and demand response is combined. Nevertheless, an important issue regarding monitoring is that the demand can be avoided at expensive hours, and this result in a reduced capacity for DFR at that specific time. This may be acceptable if monitoring is well-developed and if other resources exist that can be activated with short notice to fulfil the requirements for frequency controlled reserves.

Several aspects on monitoring are analysed in WP3 (Togeby et al., 2008).

Synergy can also exist between DFR and voltage control. Voltage problems usually happen in distribution networks due to reasons like extra loads, faults or high penetration of distributed generation, e.g. wind. Similar to DFR, by installing with control circuits, the heating or cooling loads can react to voltage dip by short interruptions, so that the local voltage can be recovered. Loads suitable for voltage control are similar to those for DFR, of which short interruption proved to be acceptable by both customers and the appliances in this project. Therefore, combining both technologies in certain loads would be feasible to supply more than one kind of services
to the system. Consequently, the business case for implementing the technologies would be largely improved.

Comparing to the frequency problem, the voltage problem is very much locally dependent, i.e. a voltage dip is experienced at different degrees (as in contrast to frequency which is universal throughout one synchronised system). Thus, the use of demand for locally voltage compensation is technically and economically more effective as compared to other methods, e.g. adjusting MVAR generation at high voltage levels.

4.3 Use in relation to islanding of distribution grids

The main focus of this project has been to use DFR in relation to interconnected grids like Nordel or UCTE. Nordel has a peak demand in the order of 70,000 MW, while UCTE is in the order of 350,000 MW. Such systems have a high inertia compared to smaller systems, e.g. the island of Bornholm (55 MW peak load). The Bornholm system operates in islanding mode when the cable to Sweden is out of service – and recently the system has experienced twice this situation because of the malfunction on the cable that links both systems. In such situation the frequency control must be delivered locally. This is not an easy task and has only been accomplished by stopping a number of large wind turbines.

Due to the Bornholm system configuration, the DFR concept is well suited to provide frequency support according to its own necessities.

Energinet.dk is studying intentional islanding of distribution grid in the Cell project (“Cell architecture for distributed generation management for the Danish electric power system”). The idea is that e.g. a 60 kV will be intentionally islanded, e.g. during system contingencies, and later on synchronize and reconnect to the main system. During this period frequency and voltage should be maintained by local resources. By use of local resources like wind power and CHP combined with high speed communication this can be fulfilled as demonstrated in Holsted (Lund, 2007). DFR can be highly needed in such a system. Not at least in the transition from connected to islanding mode quick response is needed to maintain frequency stability. DFR can deliver this. Especially DFR with integrated control (Type II) can be suitable, since also over frequencies can be dealt with (extra demand).

In Nordel the requirements for frequency controlled disturbance reserves are 1,000 MW. This is around 1-2% of the total demand. In relation to smaller islanding systems a higher fraction is needed. For the Bornholm system, preliminary studies indicate (James-Smith and Togeby, 2007) that in the order of 6 MW (~15%) of controllable load could help to balance the variance from demand and wind turbines. In smaller islanding cell quick reserves in the order of the maximum import/export at the moment for
islanding would be needed. This could result in 25-50% load as DFR. One viable option for DFR applications into systems prone to islanding condition can be to have a wider frequency deviation during islanding mode. The normal range in interconnected mode of +/- 0.1 Hz could be multiplied by 2 or 5 in islanding mode. This procedure requires coordination with the control of the local generation units.

4.4 Potential in the Nordic countries

In Togeby et al (2006) the potential and attractive issues of DFR in accordance to the Eastern Danish electric sector are presented. Electricity demand corresponding to 218 MW have been found in residential demand – more than needed for frequency controlled disturbance reserves. The 218 MW is the yearly average for cold appliances (91 MW, refrigerators, freezers), and wet appliances (65 MW, washing machines, tumble driers, dish washers) and for electric heating (62 MW). The electric heating is varying from a few MW (the average consumption for heat hot water on a summer night) to 120-200 MW (in winter). The wet appliances have little seasonal variation, but a considerable variation during day/night and weekdays/weekends.

Direct electric heating is well suited for DFR because it can be disconnected and reconnected without delay and many times per day. Direct electric heating is much more frequent in the other Nordic countries, than in Denmark.

More than 3.000.000 houses in the Nordic area are heated by electric heating. For each degree the temperature decreases, the Nordic electricity demand increases with 600 MW. In total, electric heating in the Nordic 10-years winter situation can be estimated to use up to 21,000 MW, corresponding to 30% of the total Nordic peak demand. At 0°C the electricity used heating is in the order of 10,000 MW (Togeby, 2005).

<table>
<thead>
<tr>
<th></th>
<th>Number of households with electric heating</th>
<th>Aggregated impact of temperature.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>125,000</td>
<td>22 MW/°C</td>
</tr>
<tr>
<td>Finland</td>
<td>600,000</td>
<td>86 MW/°C</td>
</tr>
<tr>
<td>Norway</td>
<td>2,300,000</td>
<td>220 MW/°C</td>
</tr>
<tr>
<td>Sweden</td>
<td>350,000</td>
<td>269 MW/°C</td>
</tr>
<tr>
<td></td>
<td>2,000,000 *</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>~ 3,375,000 – 5,375,000</td>
<td>597 MW/°C</td>
</tr>
</tbody>
</table>

* Electricity in combination with other source

Table 1. Nordel analysis of temperature dependence. Based on data for year 2000-2005. A model of the hourly demand has been used. The model includes a detailed description of the daily and yearly load curves (Togeby, 2005).

The total requirement for frequency controlled disturbance reserves are 1,000 MW in Nordel. Even at moderate cold temperatures the electricity used for heating is much larger. If 5% of all electric heating is implemented with DFR this could deliver all the
needed frequency controlled disturbance reserves at the coldest 10 years winter – decreasing to 0 MW in summer. The available capacity from electric heating can be estimated based on temperature and calendar data.

Concerning other end uses like refrigeration, freezers, pumps etc. these can be expected to exist in the same amount that in Denmark (proportional to population). The values presented in Figure 1 must be considered as an indicator of the Nordel potential for DFR in the residential areas. There are other sectors where there is a big potential for the usage of the DFR technology, such as the industrial one e.g. in metal industry (short disconnection of smelters).

Figure 1. Estimates of potentials for DFR in the residential sector in Nordel area. The indicated effect is the yearly average.

4.5 Practical stepwise implementing

Full implementation of DFR should be conducted in a stepwise plan of several phases as presented in the figure below.

Figure 2. Stepwise plan for DFR implementation
The 4.th step, TSO agreement on framework for using DFR, could include requirements about monitoring (e.g. sample size for detailed measurements), procedures for balancing DFR with traditional reserves, and a policy about a balanced use of stable (e.g. freezers) and varying DFR resources (e.g. electric heating). Also the payment structure should be decided, e.g. offering a standardised up-front payment for appliances with DFR. The TSO agreement should be closely coordinated with Nordel and UCTE.

4.6 Demonstration project

This project (phase 1) is focused on general design issues related to DFR and to test the attractiveness of it to the Danish market. While these results are positive it is still evident that more work has to done before a full scale implementation can take place. Many practical issues are still open. These include issues on the control side of the DFR, e.g. practical frequency detection, noise filtering, speed of relay etc. Also some critical design questions remain on the appliance side. These are very important matters which, depending of the design, will give a stable and efficient operation of the appliances. To face these problems, some examples related to design are presented below. These could be tested in a demonstrations project (phase 2).

2.6.1 Heat pumps

Due to its design and application, heat pumps can act as DFR. As for other thermal end uses the thermal inertia of buildings makes it possible to disconnect the heat delivery for short periods without loss of comfort. In Denmark the government will promote the uses of 100,000 heat pumps to reduce oil consumption for heating purposes.

The main electricity consumption in relation to heat pumps is for the compressor (typically 1-5 kW for a heat pump for a single family house). Other electricity demands include circulation pumps, ventilators (for heat pumps using outdoor air as heat sink), and electric heating as back up and peak supply (typically 1-5 kW, but with few active hours per year). Compressors can be on/off controlled or can be controlled with variable speed. Variable speed compressors can deliver a stable heat supply even at part load and can maintain constant temperature differences in evaporator and condenser.

For on/off controlled compressors a special design issue is related to the reconnection. Compressors can be disconnected within a few seconds, but reconnection can only take place after a certain rest period. Starting the compressor before pressure in evaporator and condenser has been equalized can over load the compressor. Without DFR the heat pumps would typically rest for minimum 30 minutes before starting.

If the heat pump is equipped with a variable speed compressor for part load, it could also response to both under and over frequency events. In situation with over frequency the speed could be increased. Such changes can be realised quickly and do not require any rest time to return to normal operation.
2.6.2 Electric floor heating

Electric heating can be supplied with an advanced control system that allow the user to control set point, check temperatures and receive alarms. Some systems can be used via an internet or mobile phone interface.

![Diagram of control system](image)

*Figure 2. Example of design question in relation to DFR for electric heating. The figure shows a standard design of a control system.*

The frequency measurement could be placed at the control unit (A). This is where the intelligent system is placed and where the integration with the temperature set-point is done (Type II: integrated control). Alternatively the frequency measurement could be placed in relation to the relay (B), which could be an example of an external control (Type I). If solution (A) is chosen one measurement can cover the whole house, however extra time delay is introduced for communicating with the relay. If wireless communication is used between the control unit and the relay, this solution could have negative impact on sensor battery life time.

4.7 References in this chapter


5

CONCLUSION AND EVALUATION

5.1 Abstract

Using demand as frequency controlled reserve (DFR) is an emerging technology which allow demand to participate actively in maintaining the system operation without reducing the energy service delivered to the customer and without need of user interaction.

The basic premise is that traditional frequency controlled reserves from power plants and interconnections with neighbouring systems can be costly, slow and not fulfil the need for future power grids with a high share of wind power and fewer central power plants, and an intention to perform flexible operation such as islanding. Electricity demands, on the other hand, have advantages as frequency reserve including fast activation speed, smooth linear activation, low expected costs, and well-dispersed in the distribution grid. The main challenge of DFR is new methods for monitoring the available capacity.

This project has investigated the technology of using electricity demands for providing frequency reserve to power systems. Within the project the potential and economy of DFR compatible loads in Denmark has been investigated, control logic has been designed, power system impact has been investigated, potential business models has been evaluated and an implementation strategy has been suggested. The project has received support from Energinet.dk’s PSO program.

The tasks and goals of the project have been successfully accomplished based on which the conclusion and future recommendation are made.

5.2 Project conclusion and evaluation

This project has developed the DFR technology that enables electricity demands to autonomously disconnect or reconnect to the grid in response to system frequency variations.

The developed DFR technology is proved to be a promising technology from several perspectives. Technically, using DFR is feasible to provide reserves and enhance power
system frequency control, while fulfilling technical requirements such as linear activation (or reconnection) according to frequency (or time). Environmentally, the DFR technology is pollution free in contrast to traditional reserves from generation side. Economically, the cost of such reserve can be low and an attractive business model providing benefit for both society and the involved parties can be established. According to the data of Eastern Denmark in 2007, the cost for frequency controlled disturbance reserve was 17 MDKK for typical 24 MW. This is equal to 700,000 DKK/MW per year. The DC connection to Germany also delivered this service at a specific price of 61,000 DKK/MW per year. A full scale use of DFR is estimated to be possible for a cost well below the 40,000 DKK/MW per year [9].

Monitoring such reserve can be realized for different needs, e.g. system operation and business implementation.

Potential exists for future development of the technology to provide voltage stability support. It has not been possible to investigate this within this project, though.

Specific conclusions of the project can be drawn according to different aspects of the DFR technology, including [1-4]:

**Need for frequency controlled reserves**
In order to maintain frequency stability i.e. the balance between generation and demand, power system operators must procure sufficient reserves. UCTE has a framework for frequency control, including primary, secondary and tertiary levels for handling imbalances between and inside control areas. Frequency control in the Nordel system is taken care by frequency controlled normal operation reserve and frequency controlled disturbance reserve. Manual regulating power is traded in the common regulation market. Imbalances on inter-regional power flow are allowed within the capacity limits. The frequency quality is lower in the Nordel system than in the larger UCTE system.

The frequency quality analysis based on actual measurement data from Phasor Measurement Unit (PMU) and other resources has demonstrated that the frequency quality in Nordic system have been decreasing in recent years due to reasons including hourly market operation and contingencies. There are many low frequency events, where DFR can be of use. E.g. 328 under frequency events with a duration longer than 5s per month (below 49.9 Hz) was recorded during the one year period from April, 2005 to March, 2006. Similar trend of decreased frequency quality is also observed in the UCTE frequency data though with a smaller magnitude.

Currently, reserves are primarily supplied from generation side at a high price. E.g. Nordel requires 1000 MW frequency controlled disturbance reserve, which is to be activated automatically when frequency drops from 49.9 to 49.5 Hz [8]. In UCTE, about 3000 MW primary reserve must be prepared [10].
In islanded system such as cell operated distribution networks, frequency control become difficult and practical experiences from Bornholm island indicate that insufficient frequency control limits the possible wind generation.

**Design**
Two types of control logics are developed for the DFR. Type I based on *external control* of appliances directly turn on and off appliances according to system frequency and pre-set thresholds. The Type I is further divided into sub types concerning different reconnection designs. Type II based on *integrated control* varies temperature set points of thermostatically controlled loads in response to frequency variations. It can handle both high and low frequencies. Based on the developed two types, more advanced control can be developed in the future.

DFR do not require communications to be installed, which substantially reduce the cost of DFR. Monitoring can be done e.g. with extra equipment for a small sample of the DFRs. For larger size loads, communication may be worthy for on-line parameterization, monitoring and business implementation, and customer’s needs for enabling/disabling the DFR function etc.

Optimal design of the DFR control should take into account the concerns of power system and the appliances. For appliances with natural operation cycles such as electric heaters, impacts to power system are the major concern. It has been demonstrated that power system requirements such as linear activation and reconnection of DFR reserves can be effectively realized by proper design of key parameters, such as disconnection set points and reconnection delays [2].

**Potential**
In Eastern Denmark for which detailed investigations has been made the potential volume of DFR compatible loads is up to 218 MW, which is much more the present 78 MW frequency controlled disturbance reserve [8]. Device types include, but are not limited to, electric water and space heating, refrigeration, freezing, washing, tumble drying, and air conditioning etc.

The potential in the overall Nordic system can be much higher due to large use of electric heating in Norway, Sweden and Finland. Thermostatically controlled load such as electric heating is of particular interests for the technology due to the large volume and the possibility of instantaneous on/off control.

**Economy**
The cost of DFR control circuit can be very low, e.g. PNNL estimates a circuit that can control 1.5 kW load costs about 20 € [1, 11]. This cost can be further reduced by mass production. With such controllers, the cost of reserves would be 603,000
DKK/MW/year for 40 W appliances, 24,000 DKK/MW/year for 1 kW appliances, and 12,000 DKK/MW/year for 2 kW appliances, based on a 8 year life time of appliances and 6% annual interest rate. These costs are much lower than the current cost of reserves in Denmark. E.g. in 2007, the frequency controlled disturbance reserve used in Eastern Denmark is typically 24 MW, and costs about 17 MDKK per year [9]. If the same amount of reserve is supplied from DFR units of 40 W capacity, the cost will be 15 MDKK with a reduction of 2 MDKK per year. With 1 kW appliances, the cost will be less than 0.6 MDKK with a reduction of 16.4 MDKK per year. With 2 kW appliances, the cost will be less than 0.3 MDKK with a reduction of 16.7 MDKK per year. Similar calculation has been made for the primary reserve in Western Denmark, and corresponding cost reduction can be up to 49.7 MDKK per year. Consider larger DFR appliances and longer life time, the total cost reduction can be much higher.

**Impact in power systems and monitoring**

It has been shown that DFR is a stabilizing technology which will improve both frequency controls in normal operation and during disturbances. The performance of DFR with respect to frequency deviations seems proportional to its amount.

In future smart power grids with cells which can go into island operation DFR can substantially improve the success for island transition and operation.

Accurate monitoring of reserves from many autonomous appliances is technically unnecessary and economically impractical. The DFR is comparable to the self-regulation of load frequency dependency taken into account today, which is estimated rather than monitored in system operation.Monitoring in case of many DFR units can be achieved by predication based on statistically sampling of a limited number of such appliances. Such a monitoring method may require the current reserve monitoring practice to extend to specify the quality requirements including accuracy of the amount and availability.

**Business model**

The business model of DFR could be either implemented through a fixed rebate of the products subsidized by power system operators or in a market approach, e.g. participate in the regulation market in the Nordic system. Communication may be but not necessarily needed for business implementation, e.g. the amount of reserve can be recorded by storage devices, and sent to system operator later through internet. The cost of having communication could be limited by utilizing existing communication system in home automation and other systems, combining DFR with other technologies including price controlled demand and demand as voltage controlled reserve.

**Implementation strategy**

Full implementation of the technology should be carried out in a stepwise plan of several phases, of which this project is the Phase I. The implementation plan also
includes phases such as demonstration of selected appliances, and formulation of new power system rules for implementing DFR etc. For the demonstration phase, major steps include,

- Development of DFR appliances of two control types, in relation to products from Danfoss heating etc
- Laboratory testing of the developed appliances
- Design and development data collation system
- Field test of the DFR appliances for a one-year period
- Analyses of data, including verification of the prediction based monitoring method
- Theoretical investigation of demand for voltage control, and synergy of DFR with other demand side technology
- Reporting and results dissemination

Environmental issue
The DFR technology is an environmental friendly technology that can facilitate further penetration of renewable energy such as wind into power systems. It is an innovation that addresses the increased political and public concern of climate change.

5.3 Recommendations for future work
It is foreseen that power systems of the future will continuously increase renewable and distributed generation. E.g. the new Danish Energy Policy recommends that 50 % of national electricity consumption should be supplied by wind generation by 2025 [5]. This trend will undoubtedly bring up challenges for system operation and control, which the developed DFR technology has a great potential to deal with. With the findings of this project, it is recommended that a demonstration project should be carried out in order to [6],

- Obtain practical experience with implementation of a DFR system based on different types of appliances and different manufacturers
- Demonstrate in real-life the ability of DFR to provide
  1. Primary control to improve frequency quality in systems with high share of wind power generation (normal frequency reserve)
  2. Fast disturbance reserve to support system security in interconnected power systems

In addition, through a demonstration project, frequency measurement device with high accuracy can be investigated; the field performance of the DFRs can be validated and evaluated; the monitoring method developed in the current project can be tested; feedbacks and customer acceptance can be collected and evaluated. Currently, the project team is in close collaboration with several manufactures i.e. Danfoss and
Vesterfost, and the network operator Øskraft at Bornholm Island for preparation of a demonstration.

The power system of the future is also desired to perform flexible operations such as intentional islanding and re-synchronization. The critical challenge in these operations is the frequency control where the DFR technology is able to facilitate. Theoretical investigation of DFR for islanding operation should be done. Practical demonstration of this can be conducted in conjunction with a demonstration phase.

Voltage instability causing serious cascading failures are experienced in the recent spate of blackouts world widely. Similar to the DFR, many demands can support voltage stability by short interruptions in events of voltage dip, which should be investigated in the future. Such a technology may have the advantage of fast activation speed, and localized therefore more effective support of reactive power.

The price responsive demand technology is another area which has been studied in many projects [7]. Many electricity loads that are suitable for different technologies are of the same kind, e.g. thermostatically controlled loads for the DFR and voltage responsive load technologies. Therefore, combining different technologies in certain loads would be feasible to supply more than one kind of services to the system. Consequently, it will be even more economically attractive to implement these technologies. Possible synergy of different demand side technologies can be investigated in the future.

5.4 References in this chapter

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