Uros Markovic

Fast Demand Response with Cooling Devices

Semester Thesis
PSL 1411

EEH – Power Systems Laboratory
Swiss Federal Institute of Technology (ETH) Zurich

Examiner: Prof. Dr. Göran Andersson
Supervisor: Dipl.-Ing. Theodor Borsche

Zurich, June 15, 2014
Abstract

Share of generating units from renewable energy sources is constantly increasing and introducing stochastic nature into the system. This results in undesirable fluctuations of mains frequency and thus, a rising need for frequency regulation services. Providing sufficient power reserves presents a complicated task and usually requires special types of fast response power plants running part-loaded. It would be a great contribution to power system efficiency if existing generators would run at its full potential, i.e. were excluded from frequency regulation. One of possible solutions for this issue, which is analyzed here, is demand side management via dynamic demand response. Presented method is based on thermostatic control of domestic cooling devices, in this case refrigerators, and modification of their energy consumption according to frequency deviation signals. Some previous studies showed that deterministic approach to demand response results in a synchronizing effect of individual appliances which leads to unacceptable levels of energy demand after steady state recovery. Other papers have addressed the issue of communication network between devices and proved that centralized method is not justified from an economic point of view. After taking these conclusions into consideration, the focus of this paper is on introducing stochastic behavior of controlled frequency responsive devices by means of designing decentralized random algorithm. This approach should enable faster regulation of system frequency during normal periods of operation, as well as avoiding critical contingency states and instability phenomena.
# Contents

List of Acronyms ........................................................................................................ v

List of Symbols........................................................................................................ vi

1 Introduction ............................................................................................................. 1
   1.1 The Need for Fast Demand-Side Regulation Resources ...................... 1
   1.2 Potential of Electricity Loads for DR.................................................... 4
   1.3 Different Approaches to DR and Implemented Method..................... 7

2 Refrigerator Modeling and Control ................................................................. 10
   2.1 Deterministic Model of a Single Refrigerator...................... 10
   2.2 Stochastic Model of a Single Refrigerator .................................... 10
   2.3 Control Algorithm........................................................................ 12
   2.4 Dynamic Temperature Setpoints ................................................... 15

3 Power System Modeling ................................................................................. 21

4 Simulation Environment ................................................................................. 24
   4.1 Matlab Model ........................................................................... 24
   4.2 System Setup ........................................................................... 25
   4.3 Refrigerator Function Block.................................................... 28
   4.4 Simulink Model Properties...................................................... 29
5 Simulation Results ........................................................................................................... 32

5.1 Normal State of Operation ...................................................................................... 32
  5.1.1 Impact of DR on System Stability ................................................................. 32
  5.1.2 Variation of the Parameter $K_s$ .................................................................. 39
  5.1.3 Variation of the DR Share in Refrigerator Devices .................................. 43
  5.1.4 Variation of the Parameter $D_{res}$ .............................................................. 46
  5.1.5 No Signal Filtering ...................................................................................... 50

5.2 Contingency ......................................................................................................... 53
  5.2.1 Fault in Swiss Control Area ......................................................................... 54
  5.2.2 Fault in EU control area ............................................................................. 60

6 Conclusion ............................................................................................................. 64

Bibliography .............................................................................................................. 65
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>TCL</td>
<td>Thermostatically Controlled Loads</td>
</tr>
<tr>
<td>AGC</td>
<td>Automatic Generation Control</td>
</tr>
<tr>
<td>DR</td>
<td>Demand response</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>CH</td>
<td>Switzerland</td>
</tr>
<tr>
<td>ENTSO-E</td>
<td>European Network of Transmission System Operators for Electricity</td>
</tr>
<tr>
<td>ENTSO-E CE</td>
<td>European Network of Transmission System Operators for Electricity - Continental Europe</td>
</tr>
</tbody>
</table>
List of Symbols

A. Parameters

\( T \) Temperature of the device
\( A \) Thermal insulation of the device
\( m \) Thermal mass of the device
\( \eta \) Coefficient of performance of the device
\( Q \) Power rating of the device
\( T^0 \) Ambient temperature
\( \lambda_1 \) Transition probability rate from ON to OFF state
\( \lambda_2 \) Transition probability rate from OFF to ON state
\( T_{OFF} \) Temperature reached by a refrigerator which is always OFF
\( T_{ON} \) Temperature reached by a refrigerator which is always ON
\( T_{des} \) Desired temperature
\( \alpha \) Thermal dispersion coefficient
\( D_{nom} \) Nominal duty cycle of appliances
\( D_{reserve} \) Available reserve for frequency regulation
\( r \) Random number
\( K_s \) Constant of proportionality
\( S_{CH} \) Nominal power of Switzerland
\( S_{EU} \) Nominal power of EU
\( p_{res.prm}^{CH} \) Reserved power for Swiss primary frequency regulation
\( p_{res.prm}^{EU} \) Reserved power for EU primary frequency regulation
\( S^{CH} \) Frequency droop of Swiss control area
\( S^{EU} \) Frequency droop of EU control area
\( t_{res.prm}^{CH} \) Response time of Swiss control area
\( t_{res.prm}^{EU} \) Response time of EU control area
\( k_{pf} \) Constant of frequency dependent loads
### p_{CH_{res.sec}}
Reserved power for Swiss secondary frequency regulation

### p_{EU_{res.sec}}
Reserved power for EU secondary frequency regulation

### C_p
Constant of proportionality

### t_{CH_{res.sec}}
Response time of Swiss control area

### t_{EU_{res.sec}}
Response time of EU control area

### r_{CH_{ramp}}
Ramp rate of Swiss control area

### r_{EU_{ramp}}
Ramp rate of EU control area

### t_{CH_{dead}}
Dead time of Swiss control area

### t_{EU_{dead}}
Dead time of EU control area

### T_{CH_t}
Turbine time constant of Swiss control area

### T_{EU_t}
Turbine time constant of EU control area

### P_{TL}
Tie-line power

### p_{CH_{DR}}
Change in DR load consumption of Swiss control area

### p_{EU_{DR}}
Change in DR load consumption of EU control area

### m
Observation window length

#### B. Indices

- **i**
  Sample index

- **k**
  Observation window index

- **t**
  Time index

#### C. Variables

- **f**
  System frequency

- **D_{des}**
  Desired duty cycle of all appliances

- **D_{prev}^{des}**
  Previously desired duty cycle of all appliances

- **D**
  Duty cycle of the device

- **d_f**
  Frequency deviation

- **d_D**
  Desired duty cycle deviation

- **k**
  Switching probability

- **S**
  State of the device

- **S_{prev}^{prev}**
  Previous state of the device

- **\Delta T^{setpoint}**
  Change in temperature setpoint

- **T_{static}^{low}**
  Static lower temperature setpoint
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{static high}}$</td>
<td>Static higher temperature setpoint</td>
</tr>
<tr>
<td>$T_{\text{dynamic low}}$</td>
<td>Dynamic lower temperature setpoint</td>
</tr>
<tr>
<td>$T_{\text{dynamic high}}$</td>
<td>Dynamic higher temperature setpoint</td>
</tr>
<tr>
<td>$D_{CH}$</td>
<td>Frequency dependent loads in Swiss control area</td>
</tr>
<tr>
<td>$D_{EU}$</td>
<td>Frequency dependent loads in EU control area</td>
</tr>
<tr>
<td>$B^{CH}$</td>
<td>Frequency bias factor of Swiss control area</td>
</tr>
<tr>
<td>$B^{EU}$</td>
<td>Frequency bias factor of EU control area</td>
</tr>
<tr>
<td>$df^{set}$</td>
<td>Frequency deviation within observation window</td>
</tr>
<tr>
<td>$df^{filtered}$</td>
<td>Filtered frequency deviation</td>
</tr>
<tr>
<td>$df^{\text{mean}}$</td>
<td>Mean of frequency deviations within observation window</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 The Need for Fast Demand-Side Regulation Resources

Electricity systems worldwide are facing fundamental changes in the coming decades, as the envisioned future grid requires reduction of carbon emissions from electricity generation and greater penetration of wind and other renewable capacity integrated in the system. However, characteristics of renewable energies such as volatility, stochasticity and intermittency present a challenge for integrating these resources into the existing grid in a large scale since the proper operation of an electric grid requires a constant power balance between supply and demand. In a power grid, the system frequency is an indicator of the balance between demand, i.e. load, and supply, i.e. generation, with the nominal frequency of 50 Hz corresponding to perfect balance between the two parameters. When consumption levels exceed the available supply, the frequency drops below 50 Hz, while in the case of excess production, the frequency rises above 50 Hz. As a result, system frequency continuously fluctuates around the nominal level and the transition system operator (TSO) ensures that the balance between demand and supply is continuously maintained, stabilizing the frequency within narrow bands around 50 Hz, by regulating the available supply. This balance has so far been maintained by utilizing reserves, usually from generation side, such as extra capacity of on-line generators, back-up generation, imports from interconnected surrounding power systems, etc. Load shedding is used as the last option by the TSO in emergency situations, where the system experiences significant frequency dips [1]. From an economic standpoint, frequency response services and reserve power are costly and any method which manages to reduce the magnitude of these services, without sacrificing system stability, is of significant importance.
Balance control represents a valuable resource from the demand side perspective, as it can actually play a very important role in this regard, with plenty of potentials to be explored. As mentioned previously, the system frequency represents the indicator of the balance between supply and demand and exists universally in the system, i.e. its signal is available to every single device connected to the grid. This means that electricity loads can be quickly turned off, in response to a frequency drop measured locally. This theory has initiated large number of research throughout the recent period, which studied the possibility of using frequency responsive loads, commonly referred to as “dynamic demand response control”, in order to reduce the amount of required reserved capacity, potentially leading to significant system costs [3]. The principal idea of these methods is to shift part of the regulation burden to the consumer side, by employing the use of intelligent domestic appliances that can alter their energy consumption. This change of load is conducted in such a way that no excessive stress is applied on the grid. However, in order for such regulation to be possible, it is required that frequency responsive services, and contracted reserves are included in the system. Not only that this presents the main requirement for acquiring fast frequency balance, but, more importantly, it provides the ability to respond to sudden power plant failures and excesses in load, which could lead to severe blackouts if not obtained within the certain time period [4]. These frequency regulation services are typically classified into three categories:

- **Primary regulation**: provided by generators and loads that respond to a change in frequency within a few seconds, ensuring that frequency deviation does not exceed the allowed threshold;

- **Secondary regulation**: provided by generators and loads responding to the system operator’s signals within 5–10 minutes, and restoring the system to nominal frequency;

- **Tertiary regulation**: provided by generators and loads that respond to the system operator’s signals in more than 15–30 minutes (typically provided by fast offline generation plants).

Primary regulating reserve is one of the most important ancillary services for maintaining the power balance in normal conditions [5]. It is deployed within one minute in order to compensate for the short term fluctuations between the balance of system load and generation units. This service has been traditionally provided by generators. The problem with this approach is that in involves
generator's slow ramping rates, thus being disabled to follow the fast changing regulation signal very well. As an example, Figure 1.1 illustrates how a coal-fired power generator fails to follow the Automatic Generation Control (AGC) setpoint commands closely [6]. This issue has been recognized in the power and energy community [7], [8].

![Figure 1.1](image.png)

**Figure 1.1** A coal-fired power generator follows AGC commands poorly [6]

Apparently conventional power plants can't follow these fast frequency deviations and modern power systems are in a need of a new method for reserve energy provision. This is where domestic appliances come to the fore, as it was discussed in paper [9]. It should be highlighted that using demand as frequency activated reserve is beneficial for power system operation in many aspects [4]:

- System operation point of view: The implementation of DR provides fast speed reserve that can be potentially activated within seconds or less, which could be essential for maintaining frequency stability and avoiding large blackouts. The fact that, in power systems, loads are usually more distributed than generation leads to the conclusion that the reserves related to the DR technique have better distribution when activated, hence increasing the potential of the grid in avoiding transmission congestions. It should be also mentioned that
introduction of DR into the system would support increase in the amount of renewable energy devices, such as wind turbine or solar panels.

- Electricity market point of view: The implementation of DR results in consumer participation in ancillary service market, therefore bringing the market closer to the full deregulation.

- Society point of view: The DR technology makes maximal use of available load recourses, as they are better utilized and expensive traditional generation is replaced by significantly cheaper power system elements, hence lowering necessary investments into the power sector. This opens up more potential for installed capacity from renewable energy sources. Consequently, DR leads to reduction of scarce natural resources and greenhouse gas emissions. This confirms that the DR technique is environmentally friendly and socially desirable.

The above analyses yet have to be examined in detail through simulation studies. Therefore, simulation models of the DR loads should be carefully built, which is the main focus of this paper. Special attention is paid to the modeling of consumer side, due to previously explained benefits of DR technique. Many household electricity loads, such as air-conditioners, heaters, refrigerators and freezers, can be turned off for a short duration without any bad impacts to the devices or customers. This great characteristic of appliances is especially applicable in case of thermostatically controlled loads (TCLs), due to their considerable volume and stable profile during the day and year. Combined with their cyclic ON/OFF switching behavior, they present ideal solution for frequency controlled reserve and flexible implementation of the DR technique.

1.2 Potential of Electricity Loads for DR

Potential for DR in power system is vast as there are many loads which can be applied with this technique. Although both industrial and domestic sectors can be exercised, in this paper the focus has been made only to those home use appliances, with remark that industrial loads could certainly be included into this analysis as well. Not every home device can be implemented with the DR technique. In order to identify loads that are compatible with the DR approach,
some of their characteristics must be reviewed, since the selection process is conducted according to following guidelines mentioned in [10]:

- Loads should be able to be disconnected for a short duration without bad influence to the appliance itself and customers

- Loads that have stable energy consumption throughout time are more valuable for providing reserve for a longer period

- Load's characteristic should provide great flexibility for implementation of the DR technique

Given the first guideline, a number of home appliances have been identified, including space and water heaters, dryers, washing machines, refrigerators, freezers, dishwashers and coffeemakers. All these devices are a necessary part of any modern household, i.e. highly concentrated within residential areas. According to [6], buildings account for 75% of the total electricity consumption with approximately equal shares between residential and commercial buildings. Buildings are hence natural candidates for providing demand-side flexibility. It has also been concluded that residential TCLs present a larger potential than commercial buildings to provide fast regulation service. This is due to the fact that with the same rated power as commercial buildings, a population of TCLs has the ability to be turned ON/OFF simultaneously, resulting in larger potential and faster ramping rate. This thermal storage potential presents a key feature for introduction of TCLs into DR scheme and it was recognized as early as the 1980s [11]–[13]. A study in [9] attempted to quantify the DR potential of those loads by calculating their average electricity consumption in households, presented in Figure 1.2 below. The number of appliances in the calculation is estimated through a questionnaire survey. The average yearly electricity consumption of a specific appliance is calculated from the average consumption of new and ten year old equipment [10]. Among those loads, thermostatically controlled appliances, including space and water heaters, refrigerators and freezers, have presented great value, due to their considerable volume and stable profile during the day and year. For example, the refrigerators have the highest electricity consumption, as shown in Figure 1.2, followed by the freezers and heaters which are all thermostatically controlled.
After determining appliances which comply with the first guideline, study is shifted to the second one, i.e. stability of the energy consumption profile. The load profile of previously mentioned TCLs is also examined according to the second guideline. Figure 1.3 shows the daily load curve of 10 refrigerators and confirms fairly stable load profile, as well as DR compatibility of refrigerators [10]. Heaters also have predictable profiles, based on e.g. temperature as studied in [14], but the load curve may have seasonal variations which results in undesirable effects. Third guideline is acknowledged in the fact that TCL appliances have special cyclic ON/OFF characteristic, thus providing large scope for DR method. This advantage is especially important and utilized in designing the control logics for the TCL appliances, discussed in the following sections.
1.3 Different Approaches to DR and Implemented Method

Many different DR ideas have been explored and analyzed so far. There are several general ideas for the control task, which differ in their complexity and, therefore, implementation costs, as described in paper [15]:

- **Decentralized approach:** Loads respond to changes in the supply in a completely autonomous, i.e. decentralized fashion, by individually monitoring the overall system frequency

- **Centralized approach:** Loads respond to external signals, e.g. from the TSO, sent through a network which connects all appliances

- **Intermediate approach:** Loads respond and set their schedules according to dynamic price information established by the utility company
Although last two methods provide much more sensitive regulation, they also require the availability of a communications infrastructure, thus significantly increasing installation costs and control system complexity. As a result, first method, i.e. decentralized approach, will be subject of analysis throughout this paper. Considering the number of available appliances and their load curve characteristics, as mentioned in 1.2, this study focuses on the problem of managing power demand and providing primary frequency regulation by means of thermostatic control of domestic refrigerators. Case studies are carried out on Switzerland's and EU's power system. This concept can also be applied to other systems, with the readjusted value of the demand response reserve according to the characteristics of the specific control zone. This paper focuses on the dynamical modifying of appliance's operational temperature and it's thresholds within a safe range, according to frequency fluctuations in the system. The main attribute of this approach to demand side management is large number of domestic refrigerators in use, as they are employed in every household. Other types of TCL appliances could also be employed in DR, e.g. freezers, water heaters etc. [18], as they also exhibit energy storage in the form of heat. Decentralized refrigerator DR approach is investigated in particular in [17] and [18]. These studies also incorporated variable temperature thresholds varied as linear functions of mains frequency deviation from its nominal value, as well as scenarios with high supply fluctuations, in order to incorporate increasing percentage of stochastic renewable power generation. Results of both analysis show that introduction of DR can successfully reduce the requirements for standing reserve. Results of paper [16] went one step further and estimated the potential economic impacts of previously mentioned control strategies in reference to the types of generating units in the system (nuclear plants, coal plants, combined cycle gas turbine plants, etc.). There is also a significant amount of studies on the topic of centralized demand side management. Some of them, such as [15] and [19], took refrigerator devices into consideration in the context of centralized model predictive control (MPC). In this case, the appliances are assumed to be connected to a communications network and are able to receive and execute commands that are generated by a central processing node. As expected, the interconnected closed-loop is far superior compared to the simpler schemes of [17] and [18], but the prospects of immediate utilization of such ideas are not justified by the extra costs that would be required for its implementation. Although more affordable and practical, decentralized feedback schemes employed in [17] and [18] can prove inadequate in achieving desired performance, as individual appliances tend to synchronize with each other, leading to unacceptable levels of energy demand, when they recover their steady-state operating temperatures [4].
appearance of such phenomena can be slow, but they do ultimately lead to unstable oscillations in the overall system frequency. The synchronization phenomenon described above was, in fact, anticipated by [17] and was also recognized in [15] and [18], even in the case where a communications infrastructure between power utilities and domestic appliances is available. Solution for this problem was suggested in paper [15], as de-synchronization strategy related to the centralized control schemes derived in [15] and [19], in which the grid operator has the ability to send control signals to the individual households. This is one of the first methods in which some form of randomization is identified as an effective strategy for solving synchronization phenomena. Since the framework of this paper consists of decentralized approach, no communication between the DR devices will be present, hence each device will act in an autonomous way by means of previously integrated algorithm. On one hand, this constraint represents a problem and complicates the DR scheme. On the other hand, it's noted that the quantity of interest is the temperature distribution of the whole population of appliances. In this sense, the problem can be formed in a probabilistic framework, in which stochastic control schemes tend to pull probability densities towards desired distributions. In this way original problem can be reduced to highly simplified case. A randomization factor can be introduced via expansion of classical hysteresis based controllers with controls that randomly jump between the ON and OFF states of the appliances when certain signal occurs. The performance of the proposed method is assessed by simulating simplified model of the Europe's power grid. Achieved results clearly verify the assumption of improved frequency regulation and reserve power dispatch control.

The need to explore the frequency regulation potential of temperature-controlled devices such as refrigerators has also been recently recognized by the European Network of Transmission System Operators for Electricity (ENTSO-E), which has proposed a new Demand Connection Code putting forward a set of connection rules enabling active demand participation [21], [4]. Practical issues around the implementation of frequency-based demand control are discussed in [22], while advantages of centralized and decentralized frequency control using DR are analyzed in [23]. The concept of decentralized DR is studied in [24] for a set of domestic loads consisted of refrigerators, which are controlled through simple disconnection of loads and reconnection after a predefined time has passed or the frequency had recovered.
Chapter 2

Refrigerator Modeling and Control

2.1 Deterministic Model of a Single Refrigerator

Standard refrigerator appliances operate in a deterministic manner, constantly switching between two states: ON and OFF. Transitions between these two states take place according to a hysteretic relay, driven by temperature. When a temperature of a device reaches its lower or upper limit, state of the device forcibly changes. Given the state of an appliance, its temperature $T(t)$ is typically assumed to evolve according to a first-order differential equation [15], [25] of the form:

$$\dot{T}(t) = -\frac{A}{m_c} \left( T(t) - T^0 + \frac{\eta Q}{A} \right)$$
when ON

$$\dot{T}(t) = -\frac{A}{m_c} \left( T(t) - T^0 \right)$$
when OFF  \hspace{1cm} (2.1)

where scalar parameters $A$, $m_c$, $\eta$ and $Q$ are used to denote the thermal insulation, the thermal mass, the coefficient of performance and the power rating of the device respectively. $T^0$ denotes the ambient temperature, which is assumed constant.

2.2 Stochastic Model of a Single Refrigerator

For the purposes of deriving a random control algorithm, the set (2.1) is extended, so that refrigerators are, instead, modeled as Markov-jump linear systems [4], [26], [27]. This means that these are switched affine systems whose driving signal is the stochastic process associated with a finite Markov
chain. This particular type of randomization is chosen because it leads to simple equations, which can be used for synthesis of control signals. In particular, we consider Markov chains with two states only, an OFF and an ON state and transition probability rates between them which are denoted by $\lambda_1$ and $\lambda_2$, respectively. By doing so, we depart from the deterministic ON/OFF switching of appliances and consider devices that randomly switch between their two operating states. Such systems are usually graphically represented as in Figure 2.1.

\begin{equation}
\dot{T}_t = -\alpha(T_t - T_{ON}) \quad \text{when ON}
\end{equation}

\begin{equation}
\dot{T}_t = -\alpha(T_t - T_{OFF}) \quad \text{when OFF}
\end{equation}

In (2.2), $T_{OFF}$ denotes the ambient temperature and $T_{ON}$ the steady-state temperature reached by a refrigerator which is always ON, while the positive coefficient $\alpha$ represents a thermal dispersion coefficient. These parameters are related to the model (2.1), by identifying

\begin{align}
\alpha &= \frac{A}{m_c} \quad T_{OFF} = T^0 \quad T_{ON} = T_{ON} - \frac{q_0}{A}
\end{align}
2.3 Control Algorithm

The idea of this paper is to implement previously described stochastic approach into refrigerator control for the purpose of DR. This is conducted through changes of variable $D_{\text{des}}$, which represents the desired duty cycle of all refrigerators on the level of the whole power system. This method is applicable, although all appliances are decentralized, since frequency variation signals around nominal value of 50 Hz, which are indicating imbalance between generation and load, are available at the terminal of each refrigerator. Signaled by each frequency variation, new desired value of the duty cycle is recalculated and each refrigerator is then randomly dispatched according to the following algorithm:

a) Recalculate the new value of the desired duty cycle.

$$D_{\text{des}} = D_{\text{nom}} + D_{\text{reserve}} \frac{df}{0.2} \tag{2.4}$$

In (2.4), $D_{\text{reserve}}$ represents available power reserved for frequency regulation. It should be fully dispatched if frequency variation reaches value of $\pm 0.2$ Hz.

b) Compute the desired change in duty cycle.

$$dD = D_{\text{des}} - D_{\text{prev}} \tag{2.5}$$

c) Compute the switching probability.

c.1) If $dD < 0$

- System requests increase in load power consumption;
- Estimate the percentage of OFF-state appliances that should be turned ON.

$$k = \frac{dD}{1 - D_{\text{prev}} \frac{df}{D_{\text{des}}} \frac{0.2}{1}} \tag{2.6}$$

c.2) Else

- System requests decrease in load power consumption;
- Estimate the percentage of ON-state appliances that should be turned OFF.

$$k = \frac{dD}{D_{\text{prev}} \frac{0.2}{D_{\text{des}}} \frac{df}{D_{\text{des}}}} \tag{2.7}$$

d) Compute new temperatures of each individual refrigerator.
d.1) If the device is ON
\[ T(t + \Delta t) = T_{ON} + (T(t) - T_{ON}) e^{-a\Delta t} \]  
(2.8)

d.2) Else
\[ T(t + \Delta t) = T_{OFF} + (T(t) - T_{OFF}) e^{-a\Delta t} \]  
(2.9)

e) Set new state of the refrigerator.

e.1) If temperature threshold is exceeded
- Change the state of the refrigerator
\[ S = \neg S^{prev} \]  
(2.10)

e.2) Else
- Apply stochastic dispatch of appliances according to switching probability \( k \).

A. Calculate random number \( r \in [0, 1] \)

B. If \( r < k \)
- Change the state of the refrigerator
\[ S = \neg S^{prev} \]  
(2.11)

C. Else
- State of the refrigerator remains the same
\[ S = S^{prev} \]  
(2.12)

Presented algorithm is based on the assumption that the large number of appliances will affect distribution of randomized values \( r \), thus enabling step e) to correctly dispatch refrigerators, i.e. as close as possible to the desired value \( D_{des} \). Implementation of this stochastic approach has significant impact on the behavior of devices, which can be observed in Figure 2.2.

First appliance is using standard deterministic control method, i.e. an ON/OFF switching process which is activated only in case of its temperature exceeding upper or lower predetermined setpoint. This results in a symmetrical state and temperature evolution, hence disabling the device in making any impact on system stability during significant frequency deviation.
Figure 2.2  Impact of DR on state evolution and temperature development of refrigerators
Second refrigerator is using proposed stochastic control algorithm and, as a result, has altered its switching trajectory three times within two hours, in comparison to the previous device. Figure 2.2 clearly shows how randomized approach overrides deterministic switching state evolution during frequency variation periods. This method presents the basis for complete model of DR applied to the power systems of Switzerland and EU, which are analyzed in the following chapters.

2.4 Dynamic Temperature Setpoints

Even with stochastic approach, deterministic characteristic of switching is still the dominate one. The main driver for change of the ON/OFF state of the appliance is temperature exceeding its threshold. This indicates that by adjusting these limits according to the frequency variation, better control of DR devices could be achieved from the deterministic point of view. This especially comes to the fore when highly responsive behavior of appliances is needed, such as in a case of a sudden power plant outage, as the initial frequency drop has to be contained as soon as possible. In order to achieve this type of controllability, following modification of the temperature setpoints should be introduced, as in Figure 2.3.

![Figure 2.3](Image)

Figure 2.3 Linearly frequency controlled temperature setpoints for DR appliances
Reasoning behind this approach is the following: In case of an imbalance between generation and consumption caused by excess in power production, frequency rises above 50 Hz. This is a signal for the increase in number of appliances which are turned ON, i.e. $D_{des} > D_{nom}$. In order to achieve this goal in a more efficient manner, setpoints could be adjusted in such a way that switching from OFF to ON state is improved, while changing state in the opposite direction is reduced. Setting linearly frequency controlled thresholds, like in Figure 2.3, leads to reduction of, both upper and lower, temperature limits. By doing so, appliances that are turned OFF are now going to reach higher temperature limit sooner and appliances that are in the ON state are going to exceed lower limits later than previously. This results in more devices being switched to ON and less being turned to OFF state, which brings the whole system faster to the desired equilibrium point, from the deterministic side of the algorithm. Graphical representation of the described scenario is depicted in Figure 2.4. Same approach can be applied in case of decrease in generation, e.g. due to power plant outage, when system frequency goes below 50 Hz.

Figure 2.4 The collective behavior of many refrigerators with frequency controlled temperature thresholds

As it was mentioned previously, increase in grid frequency above 50 Hz results in a higher demand for ON units, i.e. $D_{des} > D_{nom}$. This means that, instead of using frequency, desired duty cycle variations can provide dynamic temperature limit adjustment. Duty cycle approach is actually more convenient, due to the characteristic ramping nature of refrigerator's temperature
development and tendency to present threshold variations as a function of
time, not frequency. The relation between duty cycle and temperature can be
observed from the Figure 2.3. as

$$\frac{dT(t)}{dt} \sim D$$  \hspace{1cm} (2.13)

Continuously, same standards are applicable to temperature setpoint variations
and can be described as follows:

$$\frac{d\Delta T_{setpoint}}{dt} \sim (D_{nom} - D_{des})$$  \hspace{1cm} (2.14)

which results in the following temperature offset

$$\Delta T_{setpoint} = K_s \int_{t}^{t+ \Delta t} (D_{nom} - D_{des}) \, dt$$  \hspace{1cm} (2.15)

In (2.15), $K_s$ is a positive constant of proportionality. Variable $D_{des}$ has a
negative sign since the increase of the total duty cycle of all appliances requires
lower temperature limits, as it was described previously. New temperature
setpoints can now be easily recalculated as deviations from predetermined
static values of lower and upper limit, $T_{low}^{static}$ and $T_{high}^{static}$ respectively, as

$$T_{low}^{dynamic} = T_{low}^{static} + \Delta T_{setpoint}$$

$$T_{high}^{dynamic} = T_{high}^{static} + \Delta T_{setpoint}$$  \hspace{1cm} (2.16)

The implementation of this method differs only slightly from the initial
version outlined in 2.3, i.e. by adding equations (2.15) and (2.16) to the step d)
of the basic algorithm, stochastic demand response with variable temperature
setpoints can be achieved. Same test refrigerator, exposed to the same sample
frequency deviation as in Figure 2.2, results in a different behavior after
realization of the new algorithm, as it is shown in Figure 2.5. Use of variable
thresholds has increased the number of state switching and shifted the
switching intervals, thus making explicit impact onto the device control system.
Variable low and high temperature setpoints indicate how frequency deviation
is affecting switching sensitivity of the appliance, i.e. how precisely are
thresholds following changes in the balance between production and
consumption and enabling DR device to help in flattening out any inequality
that could potentially lead to a contingency or blackout.
As mentioned previously, dynamic temperature limits are especially effective in the short-term, i.e. immediately after contingency in the system. One similar case is presented in Figure 2.6, where performance of the algorithm was assessed in the case of a sudden jump of frequency from 50 Hz to 50.2 Hz (equivalent to the large unexpected decrease in demand or increase in
production). The duration of the step signal was 15 min, after which the frequency signal recovered to the original levels in a ramp fashion, with the recovery period lasting 10 min. As expected, the results depicted in Figure 2.6 demonstrate the superiority of the dynamic threshold method when compared to the static one. The constant barriers have no ability to follow sudden step-up of frequency and limit the refrigerator to the same switching routine, independent of the state of the power system. On the other hand, dynamical adjustment of setpoints.
Figure 2.6  Impact of variable temperature setpoints on switching behavior of the refrigerator during contingency

responds instantaneously to the contingency by decreasing both $T_{\text{low}}$ and $T_{\text{high}}$ in order to increase power consumption of appliance. As a result, refrigerator is forcibly turned on much prior to reaching its upper temperature limitation, enabling the power system to restore normal state of operation.

It should be mentioned that, even though very effective in the short term, these strategies eventually could lead to unstable overall behavior of closed-loop system [4]. This phenomenon takes the following two different forms:

- Long term phase synchronization of refrigerators: Even non identical refrigerators, with duty cycles of comparable duration, will tend to asymptotically synchronize their oscillations, causing the so called phase-locking phenomenon [28];

- Uncontrolled modifications of the population's temperature distribution: The uniform-in-phase distribution (which one expects of a population of devices that were initially switched on at random times) gets unpredictably modified by the occurrence of frequency disturbance and leads to significant oscillations in power demand [29].
Chapter 3

Power System Modeling

We now proceed to the stability analysis of a large population of refrigerators, governed by the random algorithm described in the previous chapter, when connected to a power supply network. As mentioned previously, analysis is initially conducted on the Switzerland’s power system. Since the goal of this study is to examine primary frequency control using demand response devices, analyzed power system will be represented using dynamic frequency model of the one-area system with primary-controlled power plants, such as the one in Figure 3.1 [30].

![Diagram of Dynamic Frequency Model](image)

**Figure 3.1** Dynamic frequency model of the power system with primary-controlled power plants (representation of Switzerland) [30]
Obviously, this type of modeling the electric power system of Switzerland has some flaws. The main issue is the fact that Switzerland is not an islanded power system, but one of the integrating parts of the synchronous area of continental Europe (ENTSO-E CE grid). If the large power system is highly meshed, like in the case of ENTSO-E, it can be divided into various "control zones" or "areas", corresponding e.g. to countries. Understanding and taking into account the interactions between these areas is therefore highly important for overcoming problems of our modeling approach and providing flawless operation of the entire system. Since taking all areas of ENTSO-E separately into DR analysis would make the problem practically unsolvable, a simplified simulation study is conducted where two areas are represented by two single bus systems with a tie-line in between them. Considering that DR of cooling devices in Switzerland is still the main goal of this analysis, as well as the fact that primary frequency control of ENTSOE-E CE is dispatched across the whole continental part of Europe in a fair share, it comes down to the conclusion that these two control zones should represent Switzerland and the rest of continental Europe, respectively. Continental Europe would be modeled in the same way as Switzerland in Figure 3.1. Power exchange $P_{T12}$ over the tie-line between two areas represents their only coupling and a feedback to each of the areas. Thus, the whole ENTSOE-E CE power system can be modeled in a simplified fashion with a two-area dynamic model depicted in Figure 3.2 [30].

Due to the fact that two systems of completely different sizes and volumes are understood and analyzed in the same way, special caution is needed in order to correctly model and quantify different parameters and variables of each control zone. Since this paper studies effects of DR on power system stability through refrigerator control, these appliances also need to be introduced into the model, separately from the other loads, because they are frequency dependable and thus, as equally participating in the primary frequency control as the rest of the control reserve units. Precise representation of all refrigerators in Europe, as well as the share of those which are included into DR technique is also a delicate task and needs to be conducted with care. All these considerations will be taken into account and discussed in detail in the following sections.
Figure 3.2  Two-area dynamic model including tie-line flows (representation of ENTSO-E CE) [30]
Chapter 4

Simulation Environment

4.1 Matlab Model

The full simulation of the stability analysis has been conducted in Matlab. Model from the Figure 3.2 has been extended with the secondary frequency control loop in both areas of the ENTSO-E CE power system, thus providing greater precision of the results and deeper and more accurate insight into the stability of the whole system. Appliances participating in the demand response have also been modeled and added into the simulation. Each of the two areas has one external Matlab function modeling for a certain number of refrigerators in that control zone. Due to the complexity of computational effort required for taking into analysis actual number of TCLs, each control zone ran the simulation for 10,000 refrigerators and then scaled their nominal power up so as to approximate the total number of those devices. Complete model was created and simulated in the Simulink Software Package, as shown in the Figure 4.1. All blocks are acquired from the Simulink Library, except for refrigerator models of Switzerland and Europe, which are specifically designed as a User-Defined Functions. Red and green colored blocks are noting the improvements of the actual model in comparison with the two-area dynamic model of Figure 3.2, i.e. fast demand response using cooling devices and secondary frequency control loop, respectively. Since Switzerland's area is much smaller than the EU's one, EU is regarded as the dominant control zone and, as a result, frequency and tie-line power signals are injected only into the EU model of power system, assuming that variations in this area have an impact on potential variations in Swiss system zone as well. Following section will go into detail analysis of characteristics and parameters of the main Simulink model segments.
Figure 4.1  Complete Matlab Simulink model of the ENTSO-E CE grid including refrigerators participating in the DR and secondary frequency control

4.2 System Setup

Matlab Simulink model from the Figure 4.1 took several assumptions in order to represent the ENTSO-E CE grid as a two-area dynamic model. Due to many simplifications involved, estimation of adequate system parameters presents a key step on a way to determining correct simulation scheme of the European continental power system. Analysis of the Swiss and EU control areas will be conducted in parallel, so all similarities and differences could be easily observed:
• Nominal (base) power

\[ S^C_{B} = 8000 \text{ GW} \]

\[ S^E_{B} = 250000 \text{ GW} \]  
(4.1)

• Primary frequency reserve

I. Reserved power

\[ P^C_{\text{res.prm}} = 80 \text{ MW} \]

\[ P^E_{\text{res.prm}} = 2920 \text{ MW} \]  
(4.2)

II. Frequency droop

\[ S^C = \frac{0.2 \text{ Hz}}{P^C_{\text{res.prm}}} \]

\[ S^E = \frac{0.2 \text{ Hz}}{P^E_{\text{res.prm}}} \]  
(4.3)

III. Response time

\[ t^C_{\text{res.prm}} = t^E_{\text{res.prm}} = 30 \text{ sec} \]  
(4.4)

• Frequency dependent loads

\[ k_{pf} = 0.015 \]

\[ D^C_{I} = \frac{1}{k_{pf} \frac{1}{S^C_{B}}} \]

\[ D^E_{I} = \frac{1}{k_{pf} \frac{1}{S^E_{B}}} \]  
(4.5)

• Secondary frequency reserve

I. Reserved power

\[ P^C_{\text{res.sec}} = 400 \text{ MW} \]

\[ P^E_{\text{res.sec}} = 14000 \text{ MW} \]  
(4.6)
II. Frequency bias factor

\[ B^{CH} = \frac{1}{s^{CH}} + \frac{1}{D_t^{CH}} \]

\[ B^{EU} = \frac{1}{s^{EU}} + \frac{1}{D_t^{EU}} \quad (4.7) \]

III. Parameters

\[ C_p = 0.17 \]

\[ T_n^{CH} = T_n^{EU} = 120 \text{ sec} \quad (4.8) \]

IV. Response time and ramp rate

\[ t_{res,sec}^{CH} = 200 \text{ sec}, \]

\[ t_{ramp}^{CH} = \frac{0.5 \% \ p_{res,sec}^{CH}}{1 \text{ sec}} \]

\[ t_{res,sec}^{EU} = 600 \text{ sec}, \]

\[ t_{ramp}^{EU} = \frac{[100 \% - (-100 \%)] \ p_{res,sec}^{CH}}{600 \text{ sec}} = \frac{1 \% \ p_{res,sec}^{CH}}{3 \text{ sec}} \quad (4.9) \]

V. Dead time - activation delay time

\[ t_{dead}^{CH} = t_{dead}^{EU} = 5 \text{ sec} \quad (4.10) \]

- Turbine dynamics

\[ T_t^{CH} = T_t^{EU} = 0.3 \text{ sec} \quad (4.11) \]

- Tie-line power

\[ P_{TL} = 533.33 \text{ MW} \quad (4.12) \]
4.3 Refrigerator Function Block

Controllable refrigerators are introduced into the Simulink model via two Matlab functions, one for each control area. Computational constraints prevent us from establishing actual number of DR appliances in each area. In order to accomplish the simulation, and still provide the stochastic nature of the algorithm, each block is modeled with 10 000 refrigerators. Every single device has the same control structure, as described in Chapter 2, and operates in a completely decentralized manner. Although logically independent, appliances are considered quite physically and technically similar. Nominal values for refrigerator parameters are given in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$2.4 \cdot 10^{-4}$</td>
<td>$1/s$</td>
</tr>
<tr>
<td>$T_{ON}$</td>
<td>$-20$</td>
<td>$°C$</td>
</tr>
<tr>
<td>$T_{OFF}$</td>
<td>$40$</td>
<td>$°C$</td>
</tr>
<tr>
<td>$T_{low}$</td>
<td>$2$</td>
<td>$°C$</td>
</tr>
<tr>
<td>$T_{high}$</td>
<td>$8$</td>
<td>$°C$</td>
</tr>
<tr>
<td>$T_{des}$</td>
<td>$5$</td>
<td>$°C$</td>
</tr>
<tr>
<td>$K_s$</td>
<td>$0.01$</td>
<td>$°C/s$</td>
</tr>
<tr>
<td>$D_{nom}$</td>
<td>$25$</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 4.1 Nominal parameters of refrigerators for simulation of the fast DR

In order to bring certain versatility into the simulation, thermal dispersion, asymptotic temperatures, as well as their thresholds,0 were randomly chosen from a [-15%, +15%] uniform window around the nominal values previously stated. The state and temperature of each individual refrigerator were also randomly initialized.

Frequency deviation signal $df$ represents the block input and is the same for both areas, as we assume that frequency is rather constant across the power system of continental Europe. Output signals $dP_{DR}^{CH}$ and $dP_{DR}^{EU}$ characterize change in load consumption of frequency controlled appliances in Switzerland and EU. They are added up to the primary control signals, thus included into primary frequency regulation system.

As mentioned previously, simulation sets are conducted for a reduced number of appliances, scaled up to the actual power level. According to analysis of the Swiss domestic power consumption done in paper [31], total refrigerator power consumption is set to $P_{DR}^{CH} = 300 MW$. Assuming that ratio of appliances in two control areas is similar to the ratio of nominal (base) powers
It can be concluded that total refrigerator power consumption of EU zone can be set to \( P_{DR}^{EU} = 31 \times 300 = 9300 \text{ MW} \). Of course, these statements can only be considered true if potentially all appliances would be under DR control. In further analysis these numbers would also be studied and readjusted according to other system assumptions.

### 4.4 Simulink Model Properties

Simulations are based on changes in load consumptions of both control areas. Due to previously described problem of modeling the whole Continental Europe as one control area, AGC signal values can’t be considered precise enough, i.e. only AGC deviations can be estimated from the performed simulations. As a result, additional input signals are required. New inputs come in a form of discrete frequency signal applied to the model during each time step and power transmitted over tie-line. Depending on system’s frequency feedback and load consumption of both control areas, i.e. power mismatch between generation and consumption, control reserve signals are dispatched in order to restore equilibrium of the system. This includes primary and secondary frequency regulation. Tie-line variable is introduced as it is used to readjust deviation of international power exchange from the schedule ones. That is the reason why Simulink model depicted in Figure 4.1 requires following input signals:

- System frequency - \( f \)
- Load consumption variation - \( \Delta P_{load}^{CH}, \Delta P_{load}^{EU} \)
- Tie-line power - \( P_{TL} \)

All the necessary data has been collected from Swissgrid for a time span of one year and implemented into the study. Actual primary and secondary reserve control signals of Swiss control zone have also been obtained and used in evaluation of our results.

Goal of the study is to analyze the impact of DR in primary frequency regulation on system stability, i.e. to observe and quantify any improvements after introducing frequency controllable appliances. Although control systems are deployed only in primary control, effects should be present in secondary regulation as well. The problem lies in the fact that the whole EU is represented
as one common control area, regulated by one TSO. This doesn't have any impact on primary regulation, since it's automatically activated by a frequency deviation signal. On the other hand, secondary control is dispatched individually by the operator of each country, which can't be taken into account with this simplified approach.

As described above, this study is concentrated on primary reserve regulation. Although DR devices can be considered as very responsive, they are still a part of domestic households, meaning that their frequency responsive ability shouldn't be exercised to the highest limits. In order to prevent excessive activation of refrigerator control, signal filtering method is applied to the input of the device. Since the goal is to reduce number of different commands sent to the appliance's control circuit, high-pass filter can be employed as a way of reducing responsiveness of the refrigerator only to high frequency fluctuations. High-pass filtering means keeping fast-changes and discarding the "gradual changes". One way of doing this, which is going to be implemented in this study, is removing the mean value from the signal, thus making it insensitive to small frequency deviations around 50 Hz. As it is impossible to estimate the average value of the whole signal set before it has actually occurred, slightly different method is introduced. Instead of calculating the mean value of the whole set, filtering is employed only as estimation of the average value of the set within the observation window, as described in the following algorithm:

a) Obtain new frequency deviation signal.

\[ df_i = df^{\text{present}} \] \hspace{1cm} (4.14)

b) Add it to the beginning of the set and drop the oldest value.

\[(\forall k \in [2, m]) \, df^{\text{set}}_k = df^{\text{set}}_{k-1} \]

\[ df^{\text{set}}_1 = df_i \] \hspace{1cm} (4.15)

c) Calculate new mean value.

c.1) If \( i < m \)
   - Estimate the average of obtained values

\[ df^{\text{mean}} = \frac{\sum_i df^{\text{set}}_i}{i} \] \hspace{1cm} (4.16)

c.2) Else
   - Estimate the average of last \( m \) values
\[ df^{\text{mean}} = \frac{\sum_{i}^{m} df^{\text{set}}}{m} \]  
(4.17)

d) Filter the input signal.
\[ df_{i}^{\text{filtered}} = df_{i} - df^{\text{mean}} \]  
(4.18)

e) Increase present index
\[ i = i + 1 \]  
(4.19)

In the model described above, \( m \) and \( i \) indicate length of observation window set and current index, respectively.

Frequency signals are obtained for each 10 seconds, hence the user function model sample time is set to the same value. According to input variation, reserve control is dispatched and new values of primary and secondary control, as well as frequency deviation, are computed for both control areas.
Chapter 5

Simulation Results

5.1 Normal State of Operation

Initial simulations were conducted for the system stability during normal operation, i.e. according to the yearly frequency deviations acquired from Swissgrid. One year simulation period combined with large number of refrigerators simulated in each control area during every cycle presents an enormous computational task. Consequently, analysis is reduced to a period of two weeks, which is assumed to be long enough to give any improvement of DR in system stability.

5.1.1 Impact of DR on System Stability

First analysis was based on an assumption that every refrigerator in Europe has DR controllability. Power reserved for DR is adjusted through variable $D_{\text{reserve}}$, as explained in (2.4). It was set to 12.5 % initially, meaning that after full dispatch of appliances (caused by frequency deviation of $\pm 0.2$ Hz) total duty cycle of refrigerators will change for $\pm 12.5$ % around the nominal value of 25 %. Results of the simulation are compared to the scenario without DR and depicted in Figures 5.1 - 5.8.

Frequency development in Figure 5.1 shows rather small impact of DR on system frequency during normal state of operation. Some improvements do exist, but can be estimated as negligible on the level of the whole power system. On the other hand, secondary control activation of both Switzerland and EU has been quite altered.
Figure 5.1  Frequency development after DR implementation and before (CH)

Figure 5.2  Secondary regulation after DR implementation and before (CH)
As expected, improvements made to the primary frequency regulation by adding DR control have changed the need for secondary power reserve, as shown in Figures 5.2 - 5.3. Swiss control area shows the same signal evolution, but with lower magnitudes, compared to the measurements obtained from Swissgrid, as a result of better primary reserve utilization. Secondary regulation results of EU control zone must be analyzed with caution, due to the previously stated problem of integrating many individual system operators under control of one TSO. Taking this into consideration, it can be concluded that EU area shows considerably higher level of sensitivity to frequency variation after implementation of DR.

**Figure 5.3**  Frequency development after and secondary regulation after DR implementation and before (EU)
Let’s now focus on behavior of appliances included in primary frequency control. Introduction of dynamic temperature setpoints, as described in 2.4, results in fluctuating upper and lower thresholds and is shown in Figure 5.5.

Figure 5.4  Temperature evolution before DR implementation and after
Observed signals represent maximum and minimum temperature level of a single device during each time step of the simulation, as well as mean and median temperature of all devices. Varying limits result in higher deviation of

![Switching ratio graphs](image)

*Figure 5.5 Total switching frequency after DR implementation and before*
all four analyzed levels, thus implicitly effecting the switching procedure of devices, which is closely related to temperature setpoints, Figures 5.5 - 5.6.

Figure 5.6  Individual hourly switching after DR implementation and before
As expected, switching ratio of appliances has increased in every sense. Percentage of total switching procedures per every time step has increased more than double and is much more versatile now. Although the change might seem over-excessive, it’s still only around 2 % per each interval, which is quite acceptable. Individual number of ON/OFF changes has also risen, but not as significantly as the previous parameter. Mean hourly change of all appliances is still lower than 4 switching operations, so it can be concluded that DR algorithm doesn’t bring unacceptable deviations from refrigerator’s safety regime. Results of Figure 5.7 show how exactly the consumption of appliances changes with DR.

Figure 5.7  Dispatch of load after DR implementation and before
Quite reasonably, load dispatch is adjusted to primary frequency control signals after implementation of DR. This leads to an increase in both magnitudes and volatility of the consumption profile. This characteristic was only obtained for Switzerland and its control zone, as the assumptions taken into account for EU control area would probably lead to inadequate conclusions from load dispatch profile.

It can be stated that introduction of DR control into all refrigerator appliances across Europe would lead to positive changes in both, frequency development and regulation reserve aspects, while the unwanted effects on refrigerator switching characteristic are kept to a minimum.

5.1.2 Variation of the Parameter $K_s$

Previous study assumed that $K_s$ was set to 0.01. Since this parameter is easily adjustable within the dynamic temperature setpoint algorithm, its variations should be considered as a way of improving DR model efficiency. Obviously, the higher value is taken, the bigger change in temperature limits will occur, i.e. DR effect would be more drastic. Several analysis were made, so impact of increase in $K_s$ could be estimated and a trade-off between highly responsive system and less stressed devices could be made. The scenario without dynamic temperature thresholds was also run through simulation. Following values for parameter $K_s$ were taken:

- $K_s = 0.05$
- $K_s = 0.1$
- $K_s = 0$

Consequences of first two changes have been encountered in regulation control dispatch, as well as in load profile of appliances, but no significant change has been observed in frequency deviation signal. Instinctively, greater values of temperature setpoints result in higher magnitude and fluctuations of refrigerator’s load, hence higher volatility and magnitude of primary and secondary control reserve. Although the responsiveness of the control system has been increased, deviations around nominal values of $T_{high}$, $T_{low}$ and $T_{des}$ are unacceptably high and do not contribute enough to frequency stability, as depicted in Figures 5.8 - 5.10. Conclusion is made that the trade off should go in the direction of lower temperature limits variation and thus, lower DR sensitivity. Of course, as it was discussed in 2.5, dynamic threshold adjustment comes to the fore in contingency scenarios, so it could be said that the results of normal operation analysis are as expected.
Figure 5.8  Temperature variations for $K_s = 0.05$ and $K_s = 0.1$
Figure 5.9  Secondary reserve activation for different values of $Ks$
Figure 5.10  Primary reserve activation and load dispatch for $Ks = 0.05$ and $Ks = 0.1$
Scenario with fixed thresholds, i.e. $K_s = 0$, is much more similar to the initial one than the previous two simulations. Only slight difference, beside temperature deviation, appears with secondary regulation dispatch, but of a small scale, as depicted in figure 5.9. This also confirms previous statement, as well as the analysis of 2.4, that dynamic setpoint adjustment doesn't play big role in the state of normal operation.

5.1.3 Variation of the DR Share in Refrigerator Devices

Previous simulations took an assumption that all devices across Europe are controllable, i.e. 100% refrigerator availability for DR program. In this section, analysis of a reduced percentage of DR share among cooling appliances will take place. Following studies were made:

- $p_{\text{available}}^{\text{DR}} = 75\% p_{\text{total}}^{\text{fridge}}$
- $p_{\text{available}}^{\text{DR}} = 50\% p_{\text{total}}^{\text{fridge}}$
- $p_{\text{available}}^{\text{DR}} = 25\% p_{\text{total}}^{\text{fridge}}$
- $p_{\text{available}}^{\text{DR}} = 0\% p_{\text{total}}^{\text{fridge}}$

Obviously, expectations are that a reduction in magnitude of regulation control signal will take place, as a consequence of a reduced load power. Results shown in Figure 5.11 - 5.12 only confirm these statements. As it can be observed, magnitudes of both signals gradually degrade from the scenario of 100% to the scenario of 0% load power available for DR. The only logical thing to do is to assume that initial implemented DR schemes will have lower power availability, somewhere in the range of last two simulations (0% - 25%), and that it would slowly increase as the time passes by and new appliances become integrated into the system, finally reaching full availability of 100%. According to this, all following studies have been conducted for the case of 100% DR share within the refrigerator devices, as the goal of this paper is to estimate best potential outcome of the integration of frequency controlled devices into the power grid.
Figure 5.11  Secondary reserve activation for different scenarios
Figure 5.12  Load dispatch of appliances for different scenarios
5.1.4 Variation of the Parameter $D_{\text{reserve}}$

In previous simulations, parameter $D_{\text{reserve}}$ was set to 12.5 %, i.e. 50 % of $D_{\text{nom}}$, as it was described in (2.4). This means that in case of frequency deviation of up to $\pm 0.2$ Hz, when all of the reserved DR capacity is activated, total duty cycle of devices will change for $\pm 12.5$ % around nominal value of 25 %, thus varying in the span of [12.5, 37.5] %. Obviously, this parameter can significantly alter DR characteristic, so it would be wise to determine its properties and impact it has on the overall system stability. Following additional studies were conducted:

- $D_{\text{reserve}} = 100\%\ D_{\text{nom}}$
- $D_{\text{reserve}} = 75\%\ D_{\text{nom}}$
- $D_{\text{reserve}} = 25\%\ D_{\text{nom}}$
- $D_{\text{reserve}} = 0\%\ D_{\text{nom}}$

Parameter $D_{\text{reserve}}$ was gradually reduced from 100 % to 0 % and changes in frequency regulation and refrigerator behavior were obtained. As results of Figures 5.13 - 5.15 show, correlation between reserved DR regulation capacity and primary and secondary control activation, as well as switching characteristic of appliances, is quite high. As observed parameter decays to zero, magnitude of secondary control activation and number of switching operations per time step reduces as well. Total load consumption of appliances also drops as we go towards lower values of $D_{\text{reserve}}$. Apparently, higher impact on power system frequency regulation can be achieved with higher values of reserved capacity for stability regulation. It should also be taken into account that the goal is not to deviate to far from the nominal value of the duty cycle in order to provide the safety of the refrigerator appliance itself. As a trade-off between these two aspects of the same problem, parameter is set to $D_{\text{reserve}} = 50\%\ D_{\text{nom}}$ in all following simulations and assumed to be the most efficient solution of them all.
Figure 5.13  Secondary reserve activation for different scenarios
Figure 5.14  Switching ratio of appliances for different scenarios
Figure 5.15  Load dispatch of appliances for different scenarios
5.1.5 No Signal Filtering

Signal filtering was introduced in 4.4 as a way of focusing control system of refrigerators only to fast and high fluctuations, in order to prevent over-excessive readjusting of the power output and reduction of its lifetime. Every conducted study in Sections 5.1.1 - 5.1.4 had the filter included into the control function of each cooling device. In order to analyze improvements brought into system with this approach, high-pass filtering was eliminated from the following simulation, as depicted in Figures 5.16 - 5.18. Results are quite obvious, as non-filtered DR completely changes behavior of cooling devices, which can be observed after

![Simulation (no filtering)](image)

**Figure 5.16** Secondary regulation and load dispatch of appliances in case of non-filtered DR
comparison with simulation results shown in Figure 5.3 - 5.7 where high-pass filtering was employed. Load response is significantly reduced, as indicated by large deviations from primary frequency control signal, presented in Figure 5.16. Temperature fluctuations are also badly effected as temperature limits and mean temperature of all appliances now go way below desired values, as the following Figure 5.17 indicates. These violations of threshold and average temperature are unacceptable and regular refrigerator can't operate under such conditions. On the other hand, switching behavior of devices depicted in Figure 5.18 isn't effected in the same manner, which is understandable considering highly variable temperature boundaries discussed previously. Mean hourly switching of all devices has increased slightly, but is still below 5 ON/OFF operations per hour which can be considered acceptable.

It can be concluded that high-pass filtering has the crucial impact on success of DR with cooling devices, as excluding it from the refrigerator model would result in devastating temperature evolution and non-responsive load dispatching. Hence, it will be implemented in every further simulation.

![Temperatures CH and EU](image)

**Figure 5.17** Temperature development of appliances in case of non-filtered DR
Figure 5.18 Switching behavior of appliances in case of non-filtered DR
5.2 Contingency

So far DR activity in normal state of operation has been studied, using previously obtained discrete frequency signals from Swissgrid. Improvements in the power system stability have been observed, mostly in power dispatch of primary and frequency reserve control, but results can’t be considered crucial for the operation of the grid. Since cooling devices are participating in frequency control, their main purpose is reduction of system instability during critical periods, i.e. contingencies. Analysis in 2.4 already indicated the importance of refrigerator DR in those situations on an example of a single device exposed to the artificial fault signal, where its fast responsiveness showed full potential.

Instead of altering frequency deviation signal, contingency will be modeled by introducing step signal as load consumption variation, i.e. $\Delta P_{\text{CH}}^\text{Load}$ and $\Delta P_{\text{EU}}^\text{Load}$ input. Artificial instability occurring one hour after initialization can be introduced as a function shown in Figure 5.19, for a case of an instability rise in Switzerland, while EU load variation is set to zero throughout the whole simulation. Similar approach can be taken for EU’s contingency as well. Faults in both control zones and influence of DR activation will be thoroughly analyzed in the following section. Analysis is focused only on first 3 hours of operation, as it is enough to give correct information on DR impact in faulty situations.

![Figure 5.19](image)

Figure 5.19  Artificial change in load consumption in case of contingency
5.2.1 Fault in Swiss Control Area

Contingency is modeled as 400 MW step change in Swiss load consumption variation after 1 hour of operation. Simulation results are depicted below in Figures 5.20 - 5.23.

Figure 5.20 Frequency evolution and reserve regulation in case of a fault
Figure 5.21  Switching operation of devices during a fault
Figure 5.22  Temperature evolution in case of a fault

Figure 5.23  Primary frequency control and load dispatch in case of a fault
It can be concluded that the responsiveness of the frequency control system is at a very high level, as well as that desired temperature bandwidth is not violated. Switching ratio close to the moment of contingency occurrence is reasonably quite high and hourly number of switching operation is acceptable, as its mean is below 5 ON/OFF changes per hour. Load dispatch of devices shows very high correlation with the primary frequency signal, indicating the potential of the DR in faulty situation. Compared with the scenario without DR, couple of observations can be made with certainty, as depicted in Figures 5.24 - 5.26:

- Reserve control signal follows frequency fluctuations more accurately (Figure 5.24)
- Load of appliances is dispatched in much better fashion (Figure 5.25)
- Switching ratio is higher after the contingency, but the difference can be approximated as acceptably small (Figure 5.26)

These conclusions lead to the confirmation of DR impact on power system stability during critical imbalances in the grid.

![Graphs showing frequency and AGC EU fluctuations with and without DR](image)

**Figure 5.24** Reserve control signal in case of a fault and a normal operation
Figure 5.25  Primary frequency control and load dispatch in both cases

Figure 5.26  Switching ratio change in case of a fault and a normal operation
Since DR has been proved as a good method for contingency situation, the goal is to estimate any improvements after changes in some settable parameters have been made. Increase in reserved capacity available for regulation is the only one worth mentioning, as setting $D_{\text{reserve}} = 100\% D_{\text{nom}}$ gives more satisfying results, with the positive differences shown in Figures 5.27 and Figure 5.28:

![Reserve control signal in case of different regulation reserve](image)

**Figure 5.27** Reserve control signal in case of different regulation reserve
As it could have been assumed, higher reservation of regulating power results in higher peaks of DR reserve control, i.e. load of devices, at the beginning of the contingency.

5.2.2 Fault in EU control area

The contingency in EU was modeled the same way as previously, with taking value of 3000 MW as a step change of the refrigerator’s load in EU. Results deviating from previous analysis of the fault are depicted in Figure 5.29 - 5.31.
Figure 5.29  Frequency evolution and reserve regulation in case of a fault
Figure 5.30  Switching operation of devices during a fault

Figure 5.31  Primary frequency control and load dispatch in case of a fault
Power system of the EU control area is much larger than the one of the Swiss area and, consequently, the impact of the DR is higher in this contingency scenario, which can be observed from the increased deviations of the frequency control signal in Switzerland, as well as the load dispatch and switching ratio. Simulation of contingency with greater power reserved for frequency provision results in the same changes as in 5.2.2, thus it's not mentioned in this section.

In general, behavior of the grid and profits from installing DR are developing similarly for both contingency scenarios, with only the magnitude of fluctuations depending on the size of the artificial fault that has occurred.
Chapter 6

Conclusion

A new algorithm for dynamic DR control of refrigerator appliances has been presented and tested in this paper. The proposed method takes probabilistic approach to the problem by designing stochastic algorithm and introducing variable, frequency dependent, temperature thresholds. Implemented control system ensures that no issue regarding synchronization of devices will occur, as sufficient diversity of temperatures among all appliances has been achieved.

Obtained simulation results confirm that proposed random controller is capable of improving regulation services during normal state of operation and, especially, restoring the power system's frequency after a severe contingency in the grid. Achieved results surpass the ones of the deterministic approach and lead to faster recovery at the end.

Future work will focus on improving the model, as several important assumptions have been taken along the way. One of possible new directions can be introducing other, more complex, methods of randomization. Other domestic appliances that exhibit energy storage in the form of heat, such as freezers and space heaters, could also be subjected to similar DR control scheme. Dynamic model of power system, i.e. two-area model, should be extended to more complex models, with higher number of control areas and tie-lines. Finally, economical impact of the DR using cooling devices also needs to be analyzed more in detail, as well as its impact on the Swiss and EU power system in total.
Bibliography


