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Master thesis

Mobile device power management for load flexibility: frequency dynamics and introduction to software aspects

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Abstract

Whereas the layout of electrical networks is reconsidering as a smart grid and the part of renewable energy is increasing, behaviours as sustainability, efficiency and reliability become a need for the current economical and energy contexts. The energy and climate policy from current European Union drivers is an incentive even more significant for this field of research whose results are actually expected.

In this context, a better management of power scattered on the grid could emerge as an interesting approach. From the MODEPOMA project, an idea is to manage the energy stored in mobile devices to provide a frequency control as a load aggregator. Among the hierarchy of frequency controls provided to the system as an ancillary service, we focus about the primary reserve whose the purpose is to stop the frequency drop.

This master thesis foremost reminds the frequency dynamics of an uncontrolled power system to highlight the need of frequency controls. We introduce the primary frequency control as primary reserve to prevent the frequency drop and stabilize the system frequency to a steady-state value. By this way, we give some basis and a benchmark for the following.

Then, we introduce the concept of power management of loads by modelling it and determining applied mechanisms. We prove the possibility to ensure the asymptotic stabilization of the system frequency and check its application through numerical simulations. We take a transmission system operator's perspective regarding to the current standards and possible integrations of the power management of loads. We finally introduce software aspects by defining requirements for an IT platform to implement the power management of loads.

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Introduction

« Almost every way we make electricity today, except for the emerging renewables and nuclear, puts out CO^2. And so, what we're going to have to do at a global scale, is create a new system. And so, we need energy miracles. »

Bill Gates

1.1 Context and motivation

Whereas the layout of electrical networks is reconsidering, behaviours as sustainability, efficiency and reliability become a need for the current economical and energy contexts. From there, we can understand the interest to think smarter about the grid: the smart grid. Today, the concept of smart grid is becoming a reality.

A such concept is not only an ideal vision of research engineers, but a real need for the today's market. We can emphasize on the energy and climate policy from European Union drivers given in [Pat11]: for 2020, we have to increase the part of renewable energy to 20% and decrease in greenhouse gas emissions to 20%, while we have to reduce dependence on energy imports. To upgrade the grid to a smart grid in Europe, it will require billions of euros.

However, sustainability through increasing of renewable energy leads to different problems.

Firstly, unpredictability of load on the grid will becomes more and more important with energy sources dependent on the weather. Today, ancillary services exist to regulate the load on the grid by performing frequency, voltage and production controls. Ancillary services allow us to get a load flexibility to match supply and demand. But, what about tomorrow? If we increase unpredictability, we have to adapt tools or create new ones to assure the load flexibility.

Secondly, the supply of renewable energy is not constant. So, what does it happen if the supply can't match the demand because of a lack of increasing renewable energy at this moment? Current solutions as gas turbines are expensive but mainly don't respect the energy and climate policy. New solutions must be considered to limit the dependence to the weather of renewable energy sources and their unreliable production.

A current way to introduce the smart grid approach in people minds is to install a smart home landscape. Thanks to an application software, using wireless technology, we can easily control all consumptions at home by a simple and centralized interface. The idea is to provide a solution to be green through a better consumption. By controlling the customer demand at home or by changing consumer behaviour and consumer expectations, we can reduce the global electrical demand. But this way doesn't solve any previous problem.

As described in [bib11a], another way currently exists on the market: the smart metering solution. The first utility of a smart meter is to record the exact consumption at regular intervals. These measurements are communicated to a public utility for monitoring and billing purposes. The second one is to be able to implement and control remotely the smart meter. This functionality introduces a smart grid approach, but that is not enough to assure a load flexibility.

A possible solution is a better power management to assure an adequate load flexibility. To manage load through the smart grid, it is important to be allowed to control a sufficient power. This power must be stored. So, we could manage power thanks an amount of batteries allowing us to inject or consume power on the grid. If renewable energy sources produce too many, we just consume power by storing it in batteries. If renewable energy sources don't supply enough, we just inject power stored in batteries.

A battery is becoming more and more a daily tool and its utility would increase for the next decades. Indeed, we can note mobile device always needs a battery to work: smart phone or laptop batteries are involved to be smaller and more efficient, and electrical vehicles are expected since many years. We can also imagine all industrial batteries. All these devices contain batteries with unused power and devices, connected on the grid, could be used for a power management. All that power may be not available tomorrow, but it will be probably one day.

The power management could be applied at different levels. A battery in connection with solar panels allows to regulate home consumption by smoothing the electrical demand curve. An industrial organization could install batteries to trade on the electricity price, reduce the cost of its consumption and sell his power reserve. An amount of scattered batteries on the grid allows to provide services as ancillary services. So, there are many possible applications and business processes with the concept of power management for load flexibility.

This idea is currently emerging. From [bib11b], we can take for instance the MILLENER[1] project in France: seven business partners aims to demonstrate smart grid interests thanks to 500 Lithium-ion batteries in connection with solar panels. Each battery has a capacity between 4 and 8 kWh, and so the global capacity is about 3 MWh. Objectives are to maximize receipted energy from solar panels, to clip production peaks and to shift the production to minimize the impact of local consumption on the grid. Another example from [bib11c] is a huge battery container with a capacity of 560 kWh designed for Hawaii. The objective is to smooth and optimize the production of renewable energy.

1.2 MODEPOMA project

MODEPOMA, for *MObile DEvice POwer MAnagement*, is a project whose the purpose is to study a power management thanks to the energy stored in batteries of mobile device. The idea is to develop a concept to provide a load flexibility for the frequency regulation market by using stored energy. By switching a mobile device from the battery to the AC adapter, or inversely, we could play on the balance between the generated power and the consumed power on the grid. As aggregator of loads, scattered batteries among the grid allow to consider a portfolio of loads.

This project is supported financially by BiR&D[2] and logistically by ID Campus.

At the beginning, four students are involved with their own master thesis. Studied fields are complementary: computer, economics, electrical and marketing. The purpose is so clearly focused on a practical aspect: build a prototype and a storage of knowledges to make it real in one year. Moreover, a business plan in the context of the *Management Immersion Program* is planned for two of them.

The first step is the business plan [JGPES11]. The studied scenario defined the load as a laptop battery and the frequency regulation market as the secondary reserve. Results make us aware about a lot of difficulties. The first one is the presence of significant barriers to enter in the secondary reserve: the power consumed by a laptop battery is too small to reach the minimal threshold required, the mobile nature of the laptop is problematic, and financial incentives lead to lose a lot of money. This conclusion forces us to think again about the MODEPOMA purpose.

As the first consequence, we don't target the secondary reserve of the frequency regulation

[1] Mille Installations de gEstion éNERgétique dans les îles françaises.

[2] Belgian industrial Research and Development, via the programme for Interdisciplinary Master of Science Thesis.

any more, but the primary reserve. As the second consequence, our purpose has to move up one level: we have a lack of solid theoretical basis on which we based to lead properly the project. My own master thesis, which was about software aspects and implementation of an IT platform, is now mainly about frequency dynamics aspects.

1.3 Purpose and outline

The purpose of this master thesis is to study the frequency dynamics in a large power system as the grid. We focus our interest on the primary reserve for the frequency regulation. We have to consider the frequency deviation while a disturbance appears in the power system and the current way to control this frequency deviation. There, the concept of MODEPOMA will be introduced and developed. Because the theoretical aspect, we assume more we manage loads whatever the source than the power of a mobile device.

From this purpose, we define the outline of the master thesis as:

- In the chapter 2, we consider an **uncontrolled power system**. We introduce concepts and differential questions allowing us to understand how a disturbance leads to a frequency deviation and why we need to introduce a frequency control.
- In the chapter 3, we consider the current frequency control: a **power system with primary frequency control**. We introduce it as an ancillary service and through existing definitions and standards. We expose the mechanisms behind the primary frequency control and its impact on the frequency deviation as a controller.
- In the chapter 4, we introduce a frequency control in the idea of the MODEPOMA project: a **power system with the power management of loads**. We develop a model to describe it and we define mechanisms about the behaviour of the power management of loads. We will focus on the stability of the frequency with a such frequency control.
- In the chapter 5, we take a **transmission system operator's perspective** by considering the current standards and possible integration of frequency control as the power management of loads. Through results from numerical simulation, we try to show if the power management of loads is of interest or not.
- In the chapter 6, we give a possible **introduction to software aspects** by defining requirements of a software support in response of a frequency dynamics' point of view.

Chapter 2

Uncontrolled power system

To manage loads through the grid as a primary reserve for the frequency regulation, we need to understand the frequency dynamics in a large electric power system. In a first approach, we consider the power system with any frequency regulation. This will allow us to introduce and to highlight how the frequency dynamics works, and the need to use a frequency regulation as the primary frequency control.

Obviously, mechanisms to describe and model the behaviour, especially the frequency dynamics, of a large electric power system as the grid are already known and discussed in many ways. The contemporary literature includes many books and articles allowing a clear understanding on the subject. However, let us note the majority of them don't dissociate the power system and the primary frequency control. We believe this distinction is a better approach, mainly for this master thesis. The reader have to keep in mind we don't reinvent the wheels. So, existing mechanisms are inspired by some references.

In this chapter, we introduce frequency dynamics with no frequency control in electric power systems by providing: (1) *an introduction about the system frequency ;* (2) *a simple model of an uncontrolled power system ;* (3) *a dynamic description of the system inertia with a power system containing synchronous machines as generators ;* (4) *a dynamic description of the frequency dependency of the loads ;* (5) *a description about the stability of a linear ordinary system and a demonstration about the asymptotic stability of the power system ;* (6) *a presentation of results collected by a numerical simulation of the model.*

2.1 The system frequency

To ensure a proper operation, an electric power system as the grid has a nominal value for the frequency which is defined for the whole area. Almost of electrical devices connected to the grid are designed to work at the nominal frequency f_0. If a disturbance leads to an excessive frequency deviation Δf, that can become highly problematic by leading a loss of generation through protections on the generators against a condition of overspeed or underspeed, or worse by leading to a global black out in the system.

$$f = f_0 + \Delta f \tag{2.1}$$

The balance on an electric power system consists to match the instantaneous generation $P_{generated}$ and consumption $P_{consumed}$ of electric power. This balance can be equated by:

$$P_{generated} = P_{consumed} \tag{2.2}$$

If an imbalance appears between the generation and consumption, the frequency does not remain at its nominal value. Because today the generated power can't be fully stored and the consumed power can't be accurately forecast, it is impossible to prevent a frequency deviation without mechanisms of control. An existing mechanism of control as the primary frequency control is introduced and discussed in the chapter 3.

The frequency on the grid is determined by synchronous machines as generators. Synchronous machines generate the electric power from a mechanical power and impose the frequency on the power system. We talk about a synchronous area, i.e. an area interconnected through alternative current. In case of imbalance between the generated power and the consumed power, the difference will affect the kinetic energy of each synchronous machine by an accelerating or a decelerating effect. This variation of kinetic energy leads to a frequency variation Δf. Synchronous machines are introduced with more details in the subsection 2.3.1.

The frequency in a large synchronous area as the European grid differs slightly by area and by synchronous machine. The figure 2.1 illustrates these differences. However, we note these differences are very small as compared to the average frequency in the system. This average frequency, called the *system frequency* f, is the frequency defined for the center of inertia of the system.

In this master thesis, we assume the synchronous machine frequency f_m corresponds to the system frequency f.

$$f_m = f \tag{2.3}$$

2.2 A model

Of our interests, we want to determine the frequency deviation Δf from a power deviation ΔP resulting from an imbalance whether by a generated power deviation or a consumed power deviation. We remind we consider the system frequency as the frequency of the power system. The frequency deviation is thus related to the system frequency.

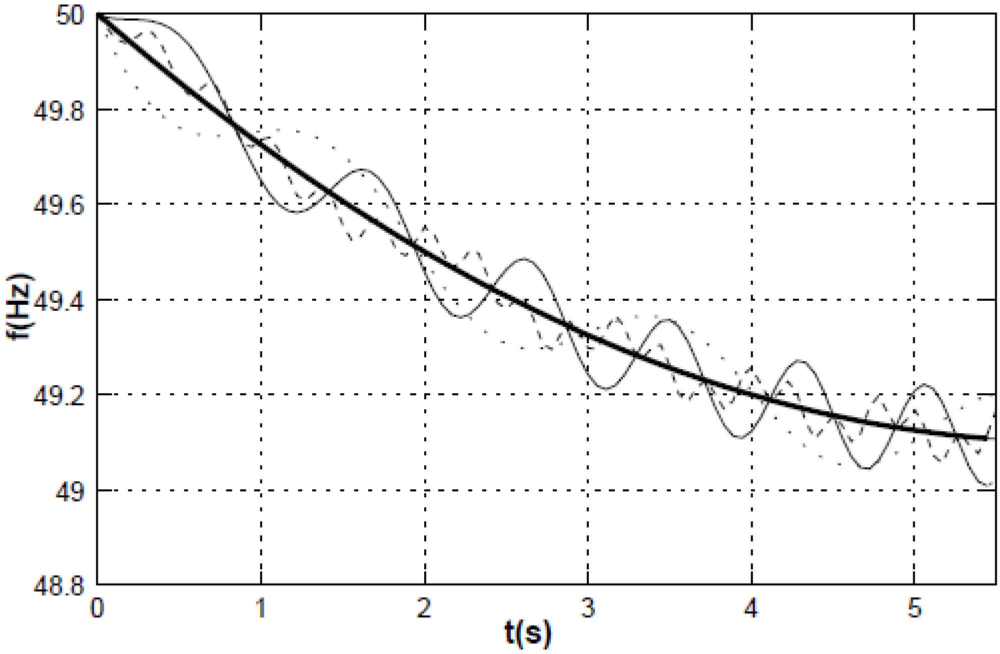

Figure 2.1: The system frequency and differences occurred for some generators, taken from [And11]

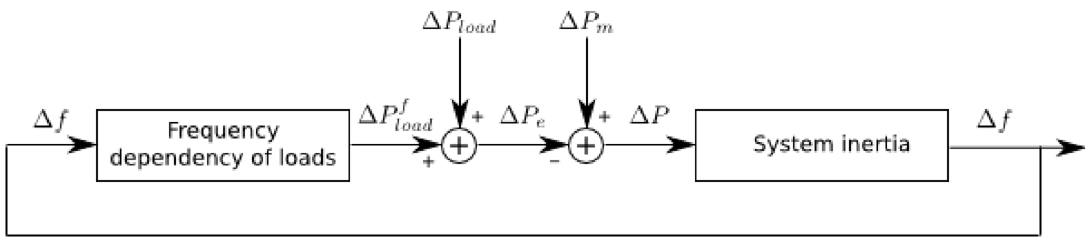

Figure 2.2: Block diagram of an uncontrolled power system

We model the uncontrolled power system as given in the figure 2.2. Foremost, we see the uncontrolled power system has two inputs and one output. The output is obviously the frequency deviation Δf. About inputs, we have a load power deviation ΔP_{load}, corresponding to a part of the consumed power, and the mechanical power deviation ΔP_m, corresponding to the generated power.

Then, we see the block-diagram can be decomposed in two parts: the system inertia and the frequency dependency of loads.

The first one takes the power deviation ΔP in the power system as an input and the frequency deviation Δf as an output. The dynamic of the system inertia is determined by the dynamic of the synchronous machines as generating units and will be described in the section 2.3. We talked about the system inertia because an imbalance on the power system will be absorbed or filled by the inertia of these synchronous machines, in particular their kinetic energy.

The second one takes the frequency deviation Δf as an input and a load power deviation ΔP^f_{load} as an output. This load power deviation mainly appears because of a consumption variation according to the frequency and corresponds to the other part of the consumed power. So, we have to consider this frequency dependency on the power system. Its dynamic is described in the section 2.4.

2.3 The system inertia

2.3.1 Synchronous machines

Synchronous machines have an important role in an electric power system as the grid. To design a model of frequency dynamics, we have to introduce and understand the involvement of these machines. All informations presented here come from [Reb08] and [VC11]. Depending of the master thesis purpose, we focus on the frequency dynamics of a synchronous machine as generating unit.

A synchronous machine consists of a rotating part, the rotor, and a fixed part, the stator. The stator produces a rotating magnetic field whose the velocity is ω_m. The rotor owns p poles arranged by pairs and produces a fixed magnetic field relative to itself. We can define the angular velocity of the rotor ω_r by:

$$\omega_m = \frac{p}{2} \cdot \omega_r \tag{2.4}$$

The electric power produced by the synchronous machine is an alternative current whose the frequency depends on the velocity of the magnetic field from the stator. The frequency can be defined by:

$$f_m = \frac{\omega_m}{2 \cdot \pi} = \frac{p}{2} \cdot \frac{\omega_r}{2 \cdot \pi} \tag{2.5}$$

While the frequency of the system is the nominal value f_0, that corresponds to an angular velocity $\omega_m = \omega_0$.

Both magnetic fields tend to align themselves and lead to the rotation of the rotor. In steady state, the rotor rotates at the same velocity than the magnetic field produced by the stator. This velocity is called the *synchronism speed*. If we try to prevent the alignment of both fields, an electromagnetic torque appears. By the application of a mechanical torque T_m on the rotor, we can use a synchronous machine to transform a mechanic energy to an electric energy, and inversely.

If we apply:

- a resistant mechanical torque: T_m is opposed to the rotation and tends to decelerate the rotation of the rotor. A restoring torque T_e appears and is directed to the rotation. In this case, the synchronous machine is used as an *electric motor*.
- a driving mechanical torque: T_m is directed to the rotation and tends to accelerate the rotation of the rotor. A restoring torque T_e appears and is opposed to the rotation. In this case, the synchronous machine is used as a *generator*.

Of our interest, a generator provide an electric power from a mechanical power. A representation is given at the Figure 2.3.

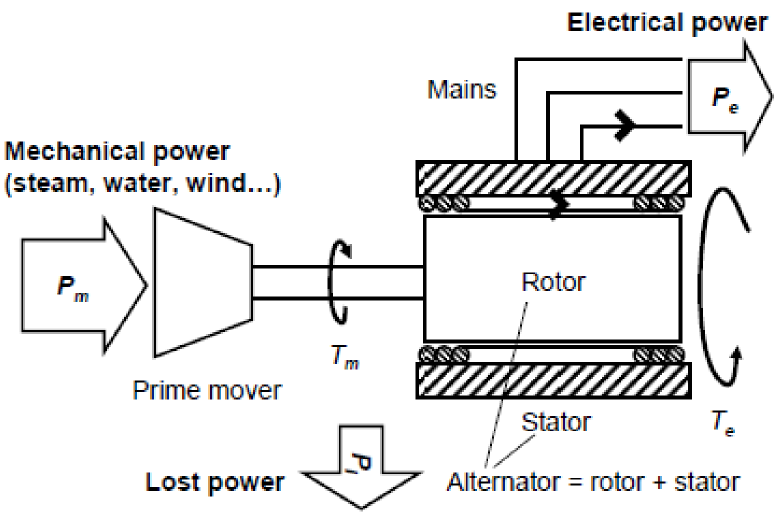

Figure 2.3: Principle of a synchronous machine as generating unit, taken from [Reb08]

On the one hand, the prime mover provides a driving mechanical torque T_m to the rotor thanks to a mechanical power P_m. On the other hand, the stator generate an electric power P_e which provides a restoring torque T_e opposed to the rotation of the rotor. We assume the lost power P_l can be neglected.

- If $T_m = T_e$: The velocity of the rotor is constant, and so the frequency is constant too.
- If $T_m > T_e$: The rotor accelerates, and so the frequency increases.
- If $T_m < T_e$: The rotor decelerates, and so the frequency decreases.

Note that there is a maximal value for the restoring torque T_e. If the mechanical torque exceeds this value, the rotor can't rotate at the *synchronism speed*: there is *loss of synchronism*. Because we work in practice with small frequency deviations Δf, we assume the mechanical torque never exceeds the maximal value for the restoring torque.

From a generator's point of view, the velocity of the rotor can also change from an imbalance in the power system between the generated power $P_{generated}$ and the consumed power $P_{consumed}$. Indeed, the generated power $P_{generated}$ is imposed by the grid. Note the electric power P_e provide by the generator is included in the generated power $P_{generated}$.

- If $P_{generated} = P_{consumed}$: The velocity of the rotor is constant, and so the frequency is constant too.
- If $P_{generated} < P_{consumed}$: The missed electric power is taken in the kinetic energy of synchronous machines. So, the rotor decelerates and the frequency decreases.
- If $P_{generated} > P_{consumed}$: The additional electric power is added to the kinetic energy of synchronous machines. So, the rotor accelerates and the frequency increases.

To link the frequency, the mechanical power and the electrical power, or equivalently the velocity of the rotor, the mechanical torque and the restoring torque, we introduce the swing equation.

2.3.2 The swing equation

The swing equation describes the dynamic behaviour of a synchronous machine from a frequency's perspective. The present development and the set of relations 2.7 to 2.25 are taken from [And11].

Because the rotor has a fixed axis including the center of inertia of the rotor, the swing equation has the following shape, where α is the angular acceleration, I the momentum of inertia and t the time:

$$T = I \cdot \alpha = I \cdot \dot{\omega} \tag{2.6}$$

The swing equation is thus an ordinary differential equation. In order to equate a model of frequency dynamics for the whole power system, we have to express the frequency deviation Δf of the power system in terms of the mechanical power deviation ΔP_m and the global load power deviation ΔP_e.

For a generator i

For a generator i, the swing equation is, in the *per unit*[1] system, where H_i is a inertia constant:

$$T_{mi}(pu) - T_{ei}(pu) = \frac{2 \cdot H_i}{\omega_0} \cdot \dot{\omega}_i \tag{2.7}$$

First, we convert torques to power values in the *per unit* system by the following relation:

$$P(pu) = T(pu) \cdot \frac{\omega_i}{\omega_0} \tag{2.8}$$

Second, we introduce the angular velocity deviation by the relation:

$$\omega_i = \omega_0 + \Delta\omega_i \tag{2.9}$$

By a temporal derivation of the equation 2.9, we obtain:

$$\dot{\omega}_i = \Delta\dot{\omega}_i \tag{2.10}$$

Third, we can express the swing equation in SI-units instead of *per unit* system. We introduce a power base S_{Bi} which represents the nominal value of the generator i.

The swing equation 2.7 expressed in *per unit* becomes in SI-units:

$$\frac{\omega_0}{\omega_i} \cdot (P_{mi} - P_{ei}) = \frac{2 \cdot H_i \cdot S_{Bi}}{\omega_0} \cdot \Delta\dot{\omega}_i \tag{2.11}$$

For n generators

Because we have to model the frequency dynamics for the whole power system, we sum all equation 2.11 for n generators.

$$\sum_{i=1}^{n} \frac{\omega_0}{\omega_i} \cdot (P_{mi} - P_{ei}) = \sum_{i=1}^{n} \frac{2 \cdot H_i \cdot S_{Bi}}{\omega_0} \cdot \Delta\dot{\omega}_i \tag{2.12}$$

We define ω as the system frequency, S_B as the total rating, H as the total inertia constant, P_m as the total mechanical power and P_e as the total electrical power:

[1] In the electrical power field, the *per unit* system expresses a quantity as a dimensionless value. This value is computed as a fraction of the initial quantity divided by a nominal basis dimensionally identical.

$$\omega = \frac{\sum_i H_i \cdot \omega_i}{\sum_i H_i} \tag{2.13}$$

$$S_B = \sum_i S_{Bi} \tag{2.14}$$

$$H = \frac{\sum_i H_i \cdot S_{Bi}}{\sum_i S_{Bi}} \tag{2.15}$$

$$P_m = \sum_i P_{mi} \tag{2.16}$$

$$P_e = \sum_i P_{ei} \tag{2.17}$$

The frequency dynamics for the center of inertia of the whole system is then described by:

$$\Delta\dot{\omega} = \frac{\omega_0^2}{2 \cdot H \cdot S_B \cdot \omega} \cdot (P_m - P_e) \tag{2.18}$$

First, we introduce the frequency deviation by the relation:

$$\Delta\omega = 2 \cdot \pi \cdot \Delta f \tag{2.19}$$

By deriving the previous relation, we obtain:

$$\Delta\dot{\omega} = 2 \cdot \pi \cdot \Delta\dot{f} \tag{2.20}$$

Second, we express the mechanical power in terms of the nominal mechanical power P_{m0}, i.e. the mechanical power for the initial balance, and mechanical power deviation.

$$P_m = P_{m0} + \Delta P_m \tag{2.21}$$

The electrical power is composed by the load power and the loss power. By defining the nominal electrical power P_{e0} as the electrical power for the initial balance, we obtain:

$$P_e = P_{e0} + \Delta P_e + \Delta P_{loss} \tag{2.22}$$

At the beginning while there is any disturbance, we have a balance between the nominal mechanical power P_{m0} and the nominal electrical power P_{e0}, i.e. $P_{m0} = P_{e0}$. Moreover, we assume there is any loss power variation, i.e. $\Delta P_{loss} = 0$.

Third, the frequency can be defined as a frequency deviation of the nominal frequency:

$$f = f_0 + \Delta f \tag{2.23}$$

Finally, we obtain the non-linear ordinary differential equation:

$$\Delta\dot{f} = \frac{f_0^2}{2 \cdot H \cdot S_B \cdot (f_0 + \Delta f)} \cdot (\Delta P_m - \Delta P_e) \tag{2.24}$$

We can linearise the equation 2.24 by considering the frequency deviation is negligible as compared to the nominal frequency, i.e. $f \approx f_0$ and $\Delta f = 0$.

$$\Delta\dot{f} = \frac{f_0}{2 \cdot H \cdot S_B} \cdot (\Delta P_m - \Delta P_e) \tag{2.25}$$

2.4 The frequency dependency of the loads

The set of relations 2.26 to 2.35 are taken from [Reb08]. Referring to [Reb08] and [And11], the power consumption of loads can be either dependent or independent of the frequency. We decompose the loads in two parts: frequency-dependent and frequency-independent loads. In the same way, the load power deviation ΔP_e can be decomposed into frequency-dependent ΔP_{load}^f and frequency-independent ΔP_{load} load power deviation.

$$\Delta P_e = \Delta P_{load}^f + \Delta P_{load} \tag{2.26}$$

For the frequency-dependency, we have two cases. The first one is a power consumption proportional to the frequency. In practice, we note the power consumed by a device decreases if the frequency decreases too, and inversely. The second one is dependent to the frequency derivative. Indeed, motors have a rotating mass which can store kinetic energy. However, there senses only in power system where industrials use large motors. We can write:

$$\Delta P_{load}^f = g(\Delta f) + h(\Delta\dot{f}) \tag{2.27}$$

First, we write the function $g(\Delta f)$, where K_l and D_l are frequency dependency constants:

$$g(\Delta f) = K_l \cdot \Delta f = \frac{1}{D_l} \cdot \Delta f \tag{2.28}$$

Second, we derive the function $h(\Delta\dot{f})$ from the kinetic energy of the rotating mass:

$$W(f) = \frac{1}{2} \cdot I \cdot (2 \cdot \pi \cdot f)^2 \tag{2.29}$$

It is the consumed power deviation by motors which leads to create a kinetic energy deviation. So, we write:

$$h(\Delta\dot{f}) = \frac{d(\Delta W)}{dt} \tag{2.30}$$

To determine the kinetic energy deviation ΔW, we consider it is a consequence from the frequency deviation Δf. So:

$$\begin{aligned}
W(f_0 + \Delta f) &= W_0 + \Delta W && (2.31)\\
&= 2 \cdot \pi^2 \cdot I \cdot (f_0 + \Delta f)^2 && (2.32)\\
&= 2 \cdot \pi^2 \cdot I \cdot f_0^2 + 4 \cdot \pi^2 \cdot I \cdot f_0 \cdot \Delta f + 2 \cdot \pi^2 \cdot I \cdot (\Delta f)^2 && (2.33)\\
&= W_0 + \frac{2 \cdot W_0}{f_0} \cdot \Delta f + \frac{W_0}{f_0^2} \cdot (\Delta f)^2 && (2.34)
\end{aligned}$$

We obtain as the kinetic energy deviation:

$$\Delta W = \frac{2 \cdot W_0}{f_0} \cdot \Delta f + \frac{W_0}{f_0^2} \cdot (\Delta f)^2 \qquad (2.35)$$

And so, the function $h(\Delta \dot{f})$ can be written:

$$h(\Delta \dot{f}) = \frac{2 \cdot W_0}{f_0} \cdot \Delta \dot{f} + \frac{2 \cdot W_0}{f_0^2} \cdot \Delta f \cdot \Delta \dot{f} \qquad (2.36)$$

Finally, the frequency-dependent load power deviation can be defined as:

$$\Delta P_{load}^{f} = \frac{1}{D_l} \cdot \Delta f + \frac{2 \cdot W_0}{f_0} \cdot \Delta \dot{f} + \frac{2 \cdot W_0}{f_0^2} \cdot \Delta f \cdot \Delta \dot{f} \qquad (2.37)$$

By substituting equations 2.27 and 2.37 in the system inertia equation 2.24, we obtain the non-linear ordinary differential equation describing the frequency dynamic of an uncontrolled power system:

$$\Delta \dot{f} = \frac{f_0^2}{(2 \cdot H \cdot S_B \cdot + W_0) \cdot (f_0 + \Delta f)} \cdot \left(\Delta P_m - \Delta P_{load} - \frac{1}{D_l} \cdot \Delta f \right) \qquad (2.38)$$

2.5 Stability

As mentioned earlier, the stability of the system frequency is very important in the case of a power system as the grid. It is of our interest to consider the stability of a such system and so its stabilization.

Intuitively, the uncontrolled power system is asymptotically stable: a frequency deviation occurs from an imbalance in the electric power system. This imbalance is filled by a variation of the global kinetic energy contained in generators. Despite a system frequency which is not at its nominal value, the power balance appears again due to the frequency dependency of the loads.

Indeed, a frequency deviation leads to a variation of the power consumption. This variation implies a load power deviation ΔP_{load}^{f} opposed to the initial disturbance. So, the disturbance should disappear and there should be again a balance between the generated and the consumed power.

For instance, a positive load power deviation ΔP_{load} leads to reduce the kinetic energy of generators. Therefore, the rotor decelerates and the system frequency decreases. If the frequency decreases, the power consumption decreases too. There is thus a load power deviation ΔP^f_{load} opposed to the load power deviation ΔP_{load}.

2.5.1 Theoretical review: stability of a linear system

The stability of a system is an inherent feature of it, and is thus independent of the input. To demonstrate the stability of a system as the uncontrolled power system, we are representing our system as a linear state space system and computing eigenvalues which allow us to highlight the property of stability.

From [AM08], a system of ordinary differential equations can be represented by a linear state space system 2.39 where we define x as the state vector, u as the control vector, i.e. inputs, y the measured signal, i.e. outputs, and A, B, C and D are constant matrices.

$$\begin{cases} \dot{x} = A \cdot x + B \cdot u \\ y = C \cdot x + D \cdot u \end{cases} \tag{2.39}$$

From [AM08], the followed theorem allows to determine the stability of a linear system.

Theorem Stability of a linear system.
The system

$$\frac{dx}{dt} = A \cdot x \tag{2.40}$$

is asymptotically stable if and only if all eigenvalues of A all have a strictly negative real part and is unstable if any eigenvalue of A has a strictly positive real part.

From [AM08], the eigenvalues of the matrix A are defined as:

$$\lambda(A) = \{s \in \mathbb{C} : \det(s \cdot I - A) = 0\} \tag{2.41}$$

The polynomial $\det(s \cdot I - A)$ *is the characteristic polynomial and the eigenvalues are its roots.*

2.5.2 Stability of the uncontrolled power system

The equation 2.38 can be linearised by considering the frequency deviation is negligible as compared to the nominal frequency, i.e. $f \approx f_0$ and $\Delta f = 0$.

$$\Delta \dot{f} = \frac{f_0}{(2 \cdot H \cdot S_B + W_0)} \cdot \left(\Delta P_m - \Delta P_{load} - \frac{1}{D_l} \cdot \Delta f \right) \tag{2.42}$$

The linearised equation 2.42 can be written in a linear state space system.

The linear state space system is:

$$\begin{cases} \dot{x} = -\frac{C}{D_l} \cdot x + C \cdot u \\ y = x \end{cases} \tag{2.43}$$

where:

$$x = \Delta f \tag{2.44}$$

$$u = \Delta P_m - \Delta P_{load} \tag{2.45}$$

$$C = \frac{f_0}{2 \cdot H \cdot S_B + W_0} \tag{2.46}$$

By identifying the constant matrix A, the characteristic equation is:

$$\lambda + \frac{C}{D_l} = 0 \tag{2.47}$$

We determine the value of the eigenvalue λ:

$$\lambda = -\frac{C}{D_l} = -\frac{f_0}{D_l \cdot (2 \cdot H \cdot S_B + W_0)} \tag{2.48}$$

Because all parameters f_0, D_l, H, S_B and W_0 are strictly positive, we always have:

$$Re(\lambda) < 0 \tag{2.49}$$

According to the theorem on the stability of a linear system, we can affirm the uncontrolled power system is always asymptotically stable.

2.6 Numerical simulation and results

With the ODE system 2.38 we defined, we can build a numerical simulation. To conduct this, we implement the ODE system in Matlab and solve it thanks to the function *ode45*. The source code is available in the appendix A.1.

A disturbance appears in the system while the balance between the generated and the consumed power is broken. That means a non-zero power deviation ΔP will lead to a frequency deviation Δf. Of our interest, we want to evaluate the theoretical frequency response f through the frequency deviation Δf.

For the numerical simulation, we consider the disturbance as a step function. In practice, we arbitrarily define the mechanical power deviation ΔP_m as equal to zero and the load power deviation ΔP_{load} as the disturbance. In theory, this choice does not matter because the main point is the global power deviation ΔP. So, a sudden increase of load or a loss of generation, and vice versa, has an equivalent effect on the frequency deviation. Indeed, we have:

$$\Delta P = \Delta P_m - \Delta P_e = \Delta P_m - \left(\Delta P_{load}^f + \Delta P_{load}\right) \tag{2.50}$$

In our model, we define the value of parameters given in the table 2.1, based on [And11].

Parameter		Value	
The total inertia constant	H	5	$[s]$
The total rating	S_B	4000	$[MW]$
The nominal frequency	f_0	50	$[Hz]$
The frequency-dependency constant	D_L	$\frac{1}{80}$	$[\frac{Hz}{MW}]$
The nominal kinetic energy	W_0	100	$[\frac{MW}{Hz}]$

Table 2.1: Values of parameters for the numerical simulation of an uncontrolled power system, based on [And11]

The variation of the load power deviation

On the figure 2.4, we can observe theoretical frequency responses of uncontrolled power system for different load power deviations.

Foremost, we can confirm the intuitive behaviour: if a positive power deviation ΔP occurs, i.e. a negative load power deviation ΔP_{load}, the frequency deviation Δf is positive and the system frequency f increases. Indeed, the generated power exceeds the consumed power. That leads to increase the kinetic energy of all generators and so the frequency of the system. We can use the same logic with a negative power deviation ΔP.

We can also observe the power deviation ΔP and the frequency deviation Δf are of the same sign. So, the load power deviation ΔP_{load} and the frequency deviation Δf are of opposite signs, which seems consistent. Furthermore, the more the power deviation ΔP is important, the greater the frequency deviation Δf is significant.

Then, the frequency variation is damped. We observe we have an over-damping, i.e. there is any oscillation on the system frequency in the system and it stabilizes at a steady state. However, a steady state with a frequency deviation of the order of Hertz is unacceptable. In the same way, it is very problematic for an electrical power system as the grid that the system frequency isn't bring back to a steady state with its nominal value.

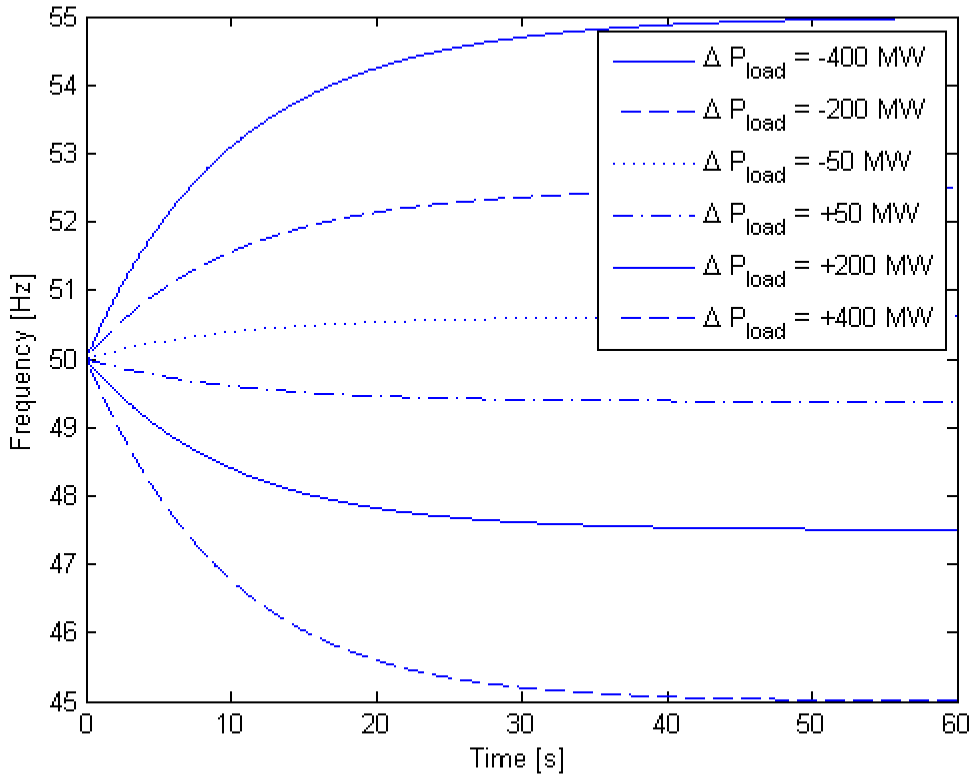

Figure 2.4: Theoretical frequency responses of uncontrolled power system, similar to [And11]

Conclusion

Results for an uncontrolled power system show us the system frequency changes whenever there is an imbalance between the generated and the consumed power, and this change remains even in asymptotic conditions. In practice, this happens all the time. It is thus necessary to establish a frequency regulation. A frequency regulation as the primary frequency control is introduced and discussed in the chapter 3.

Chapter 3

Power system with primary frequency control

Because a frequency deviation appears with an imbalance on the grid, there exist a hierarchy of controls for keeping the system frequency to its nominal value. We focus here on the bottom layer of this hierarchy which is named "primary frequency control".

In the same way that the uncontrolled power system discussed in the chapter 2, mechanisms to describe and model the behaviour of the primary frequency control are already known and discussed in the literature. We focus on it to introduce and recall what already exists for the primary reserve.

More particularly, this allows us to introduce definitions and standards currently in application. Although rules can change, it is important to realize the limitations inherent to these rules and the current approach. By understanding how works the primary frequency control, we could compare fundamentals with a power management of loads.

In this chapter, we provide an overview about the primary frequency control by: (1) *an introduction of the primary frequency control as an ancillary service ;* (2) *an introduction of definitions and standards from UCTE and the Belgian TSO for primary frequency control ;* (3) *a simple model of a power system with primary frequency control ;* (4) *a dynamic description of mechanisms for the control loop and the turbine dynamics ;* (5) *a demonstration about the stability of the power system ;* (6) *a presentation of results collected by a numerical simulation of the model.*

3.1 Primary frequency control as an ancillary service

To roughly describe the primary frequency control as an ancillary service, we take documents [Reb08], [RK05], [And11] and [UCT09] as references.

In an electric power system as the European grid, users expect some parameters as frequency are close to their nominal value. Indeed, most devices work for a specific frequency. It is thus important to meet the nominal value in the power system all the time.

There needs services as frequency control on the power system. If the control is provided by the system itself, we call it *system services*. If the control is provided by some users, we call it *ancillary services*. The figure 3.1 illustrates the distinction between them. More generally, ancillary services are composed by frequency and voltage control, and black start.

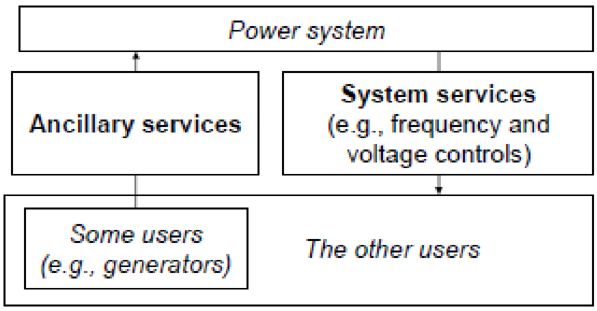

Figure 3.1: Distinction between ancillary and system services, taken from [Reb08]

All controls in an electric power system consist to balance the electric power produced by generators and consumed by loads. If the balance is broken, there appears frequency deviations in the power system. A too large frequency deviation is dangerous for all electric devices working with a nominal value of the frequency. If the frequency deviation does not control, this will lead to a global black out and to damage electric devices. The frequency control consists to keep the frequency deviation within acceptable limits by changing the power supplied or consumed.

The frequency control in Europe can be decomposed into three levels. Using UCTE[1] terminology, these levels are called primary, secondary and tertiary control. Each level of control has its own power reserve. The figure 3.2 illustrates the framework for frequency regulation in Europe. Because we focus on the primary control, we introduce it with more details.

The European grid is a synchronous area, so we consider the frequency is the same over the whole area. If there is a frequency deviation, the *primary control* aims to stabilize the frequency to a new value by maintaining the balance between supply and demand on the whole synchronous area. This prevents to increase more and more the frequency deviation, but does not restore the system frequency. The primary control is automatic, i.e. the primary reserve is delivered in opposition to any frequency change.

[1] The Union for the Co-ordination of Transmission of Electricity (UCTE) is a part of the European Network of Transmission System Operators for Electricity (ENTSO-E) which is an association composed by the overall European Transmission System Operators (TSOs).

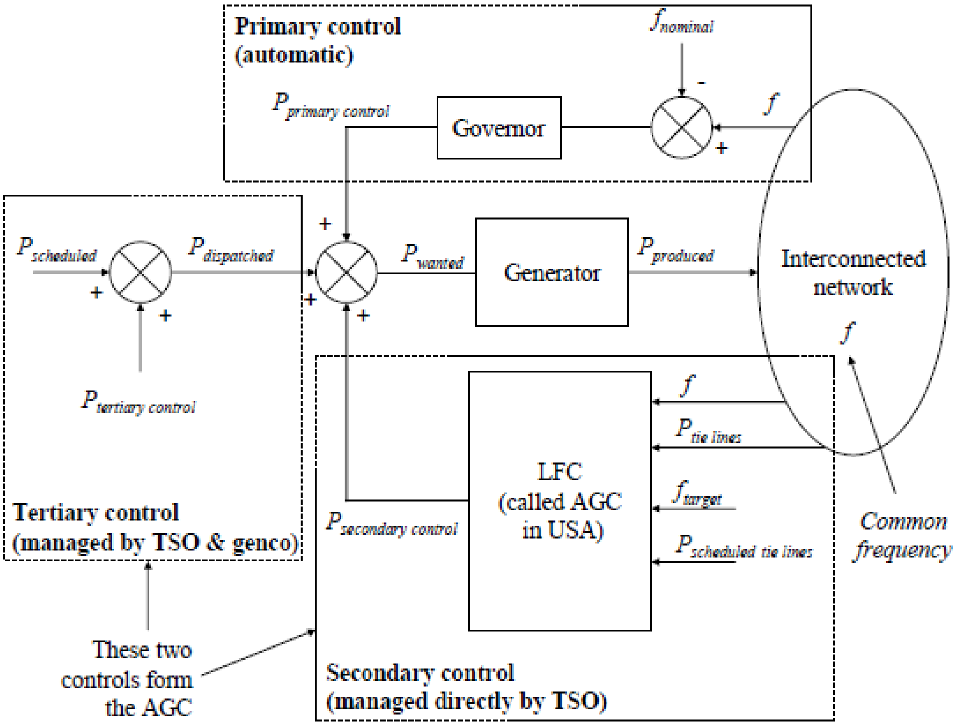

Figure 3.2: Framework for frequency control in Europe, taken from [RK05]

The figure 3.3 illustrates the frequency deviation during the process of stabilization. The dynamic frequency deviation is the maximum deviation allowed in the power system, and the quasi-steady-state is the frequency deviation between the new frequency and the target (nominal) frequency.

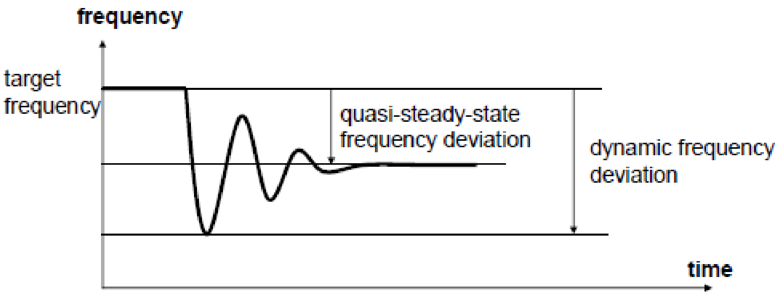

Figure 3.3: Dynamic and quasi-steady-state frequency deviation, taken from [Reb08]

The *secondary control* aims to bring back to the nominal frequency by maintaining the balance between supply and demand on a control area. So, the objective is to restore the system frequency. It is introduced and managed by the TSO in charge of the control area. The secondary reserve is activated after the primary reserve.

The *tertiary control* is a manual control activated by the TSO if the secondary reserve is not sufficient or in supplement to the secondary reserve in response of a large incident.

The figure 3.4 illustrates the frequency deviation and the activation of reserves in a time perspective.

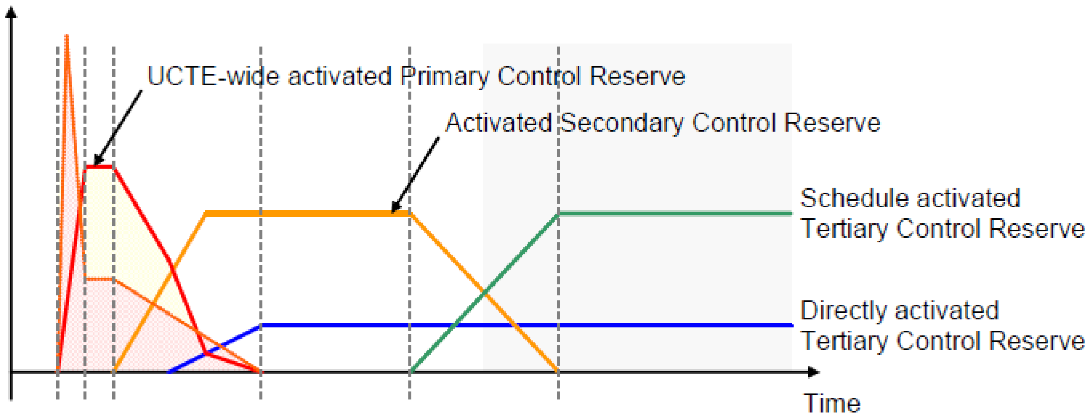

Figure 3.4: The frequency deviation and the activation of reserves, taken from [UCT09]

For the three kinds of control, we can separate the frequency regulation in two kinds of regulation: an upward regulation and a downward regulation.

While an imbalance on the grid is derived from a consumed power upper than the generated power, there needs to inject power in the grid to cope with the imbalance: it is so-called an upward regulation. Inversely, there needs to remove power from the grid if the generated power is upper than the consumed power, and it is so-called a downward regulation.

3.2 Definitions and standards

Definitions and standards are defined by UCTE and the Belgian TSO in technical manuals [UCT09] and [Eli08]. We mention those allowing us to understand how primary frequency control works.

3.2.1 UCTE definitions

To standardize definitions towards the whole synchronous area, UCTE specifies it.

The *nominal frequency* f_0 in the synchronous area is defined equal to 50.000 Hz. With a measured frequency f, the *frequency deviation* is defined as:

$$\Delta f = f - f_0$$

The *activation of the primary control* is triggered when the frequency deviation exceeds ± 20 mHz. If the frequency deviation exceeds ± 200 mHz, there is *full activation of the* *primary reserve.*

The *maximum quasi-steady-state frequency* is defined equal to ±180 mHz, while the *maximum dynamic frequency* is defined equal to ±800 mHz.

To ensure previous definitions, UCTE defines a maximum instantaneous power deviation. The power deviation is the difference between supply and demand. The *maximum instantaneous power deviation* is defined to be 3,000 MW for the whole synchronous area. Each TSO, responsible for a control area, have to reserve a part of this maximum instantaneous power deviation.

3.2.2 UCTE standards

UCTE standards introduce following characteristics for generators performing primary frequency control.

The *accuracy of frequency measurements* must be at least 10 mHz. The *measurement cycle for frequency observation* in a control area must be in the range of 1 to 10 seconds. The minimal time is strongly recommended.

The *physical deployment* must start a few seconds after the measurement of the frequency deviation. A generator must be able to deploy at least 50% of its primary reserve at 15 seconds, and all primary reserve at 30 seconds. The primary reserve must be activated until the frequency deviation is offset by the secondary and tertiary reserves. In the worst case, the primary reserve has to be delivered for a *minimum delay* of at least 15 minutes.

The *primary reserve* must be available continuously without interruption and must be included in an only one control area. So, there is not split of a primary reserve between different control areas.

3.2.3 Belgian TSO standards

The Belgian TSO is Elia. As seen above, UCTE defines the maximum instantaneous power deviation to 3,000 MW for the primary reserve. The Belgium's volume for primary reserve is defined equal to 100 MW. This means Elia must reserve a power of 100 MW at all moments to do frequency control.

By the ancillary services' definition, any UCTE user grid can provide a service as primary frequency control if technical characteristics of its facilities respect UCTE definitions and standards. A contract has to be drawn between the user and Elia.

The current process between the user and Elia happens in three steps:

J-1: The user provides to Elia at each quarter-hour: the available primary reserve, a list of generating units involving in the primary reserve, and the ratio of primary reserve for each facility.

J: The user specifies to Elia in real-time: the primary reserve that can be provided and facilities involving in primary frequency control.

J+1: Elia sends to the user: a frequency-variation report to determine if the primary reserve is adequately activated for frequency control.

3.3 A model

The primary frequency control is inserted as a loop to the uncontrolled power system. Its role is thus clearly to act as a controller in the power system thanks to a feedback. The figure 3.5 gives the block-diagram of the power system with primary frequency control.

We see the system has one input, the load power deviation ΔP_{load}, and one output, the frequency deviation Δf. In contrast to the model for the uncontrolled power system, we lose an input as the mechanical power deviation ΔP_m which is now managed by the primary frequency control.

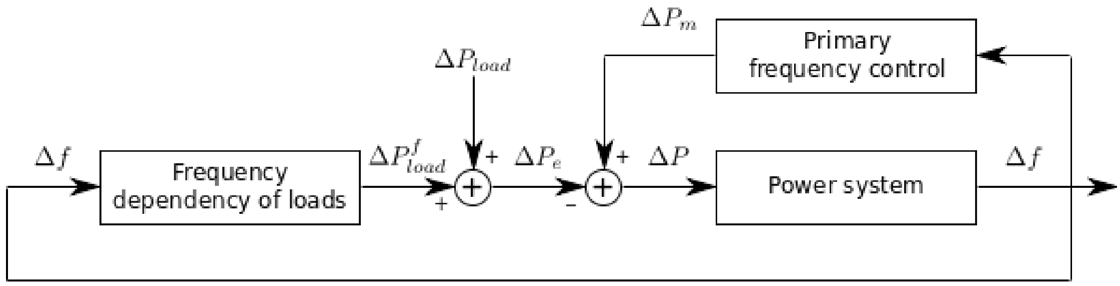

Figure 3.5: Block diagram of a power system with primary frequency control

The primary frequency control takes the frequency deviation Δf as an input and the mechanical power deviation ΔP_m as an output. In other words, the primary frequency control consists to change the mechanical power deviation ΔP_m from the frequency deviation Δf to reduce and stop the frequency drop.

The block-diagram of the primary frequency control is given in the figure 3.6. We see it can be decomposed in two parts: the control loop and the turbine dynamics.

The control loop determines the mechanical power $\Delta P_m^{f,set}$ to apply according to the frequency deviation. That is done automatically at every moment. By adding the nominal value for the mechanical power deviation ΔP_{m0}^{set}, we obtain the mechanical power deviation

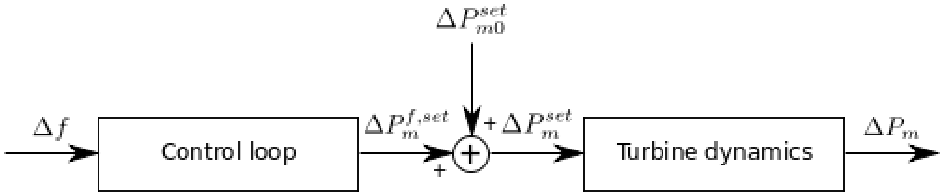

Figure 3.6: Block diagram of the primary frequency control

ΔP_m^{set} to apply to turbines of synchronous machines.

However, a turbine can't just instantaneously apply the mechanical power ΔP_m^{set}. So, we have to consider the turbine dynamics to determine the mechanical power ΔP_m effectively applied.

3.4 The primary frequency control

3.4.1 The control loop

A P-controller

The control loop is typically a *P-controller* using an error feedback. By definition of it from [AM08], we can equate the control loop by an equation of the following shape, with u as the control signal for the system to control, e as the error and k_p as the proportional gain:

$$u = k_p \cdot e \tag{3.1}$$

We can identify the different terms. The error e is defined by the difference between the nominal frequency and the measured frequency, i.e. the system frequency f.

$$e = f_0 - f = -(f - f_0) = -\Delta f \tag{3.2}$$

The control signal u is the mechanical power deviation to apply according to the frequency deviation, i.e. the difference between the nominal mechanical power to set and the mechanical power deviation to set.

$$u = P_{m0}^{f,set} - P_m^{f,set} = \Delta P_m^{f,set} \tag{3.3}$$

The proportional gain k_p is defined, with S as the speed droop characteristic:

$$k_p = \frac{1}{S} \tag{3.4}$$

By substituting equations 3.2, 3.3 and 4.12 in 3.1, we obtain:

$$\Delta P_m^{f,set} = -\frac{1}{S} \cdot \Delta f \tag{3.5}$$

By the proportional nature of the controller, we can explain the presence of a steady-state frequency deviation as a static error. Reminder, the steady-state frequency deviation was introduced at the figure 3.3. This also explains why the primary frequency control aims to reduce and stop the frequency drop and not to bring back the frequency to its nominal value.

The speed droop characteristic

From the equation 3.5, we can write in the SI-system, with a droop expressed in $\frac{\text{Hz}}{\text{MW}}$:

$$S = -\frac{\Delta f}{\Delta P_m^{f,set}} = -\frac{f_0 - f}{P_{m0}^{f,set} - P_m^{f,set}} \tag{3.6}$$

In the *per unit* system, the previous equation can be written, with a droop expressed in %:

$$S = -\frac{\frac{f_0 - f}{f_0}}{\frac{P_{m0}^{f,set} - P_m^{f,set}}{\Delta P_{m0}^{f,set}}} \tag{3.7}$$

For a generating unit, the speed droop characteristic is an parameter which determine the linear relation between the frequency deviation Δf and the mechanical power deviation $\Delta P_m^{f,set}$ to apply. In others words, the droop determines the generating unit's response. For a low droop, the response will be strong, and inversely.

For example, the figure 3.7 displays two different droop parameters. The droop a has a stronger response than the droop b. The speed droop characteristic represents the set of all possible points $(P_m^{f,set}, f)$ of a turbine. We can choose the behaviour of a generating unit by fixing values f_0, $P_{m0}^{f,set}$ and S.

In Europe, the value of the speed droop characteristic for a turbine is usually between 2% and 4%, in *per unit* system. This value is inherent to the turbine nature.

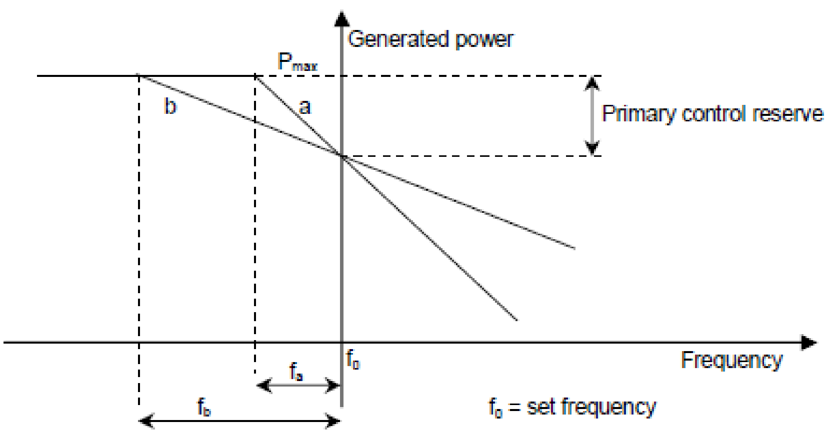

Figure 3.7: Graphical display of the speed droop characteristic, taken from [Ges10]

3.4.2 The turbine dynamics

We assume the turbine dynamics leads to a damping of the generated mechanical power with a certain time constant τ_t. We consider the turbine dynamics is composed by a *I-controller* using an error feedback as a turbine controller and the turbine itself. In the frequency domain, we set them $C(s)$ and $G(s)$ respectively.

We obtain:

$$\Delta P_m = \frac{C(s) \cdot G(s)}{1 + C(s) \cdot G(s)} \cdot \Delta P_m^{f,set} = \frac{G(s)}{G(s) + \frac{1}{C(s)}} \cdot \Delta P_m^{f,set} \tag{3.8}$$

By definition of it from [AM08], we can equate the turbine controller by an equation of the following shape, with k_i as the integral gain or T_i as the time constant, and s the Laplace variable:

$$C(s) = \frac{k_i}{s} = \frac{1}{T_i \cdot s} \tag{3.9}$$

We identify the time constant T_i as the turbine time constant τ_t. We consider the turbine is neglected, i.e. $G(s) = 1$. By substituting the equation 3.9 in 3.8, we have in the frequency domain:

$$\Delta P_m = \frac{1}{1 + \tau_t \cdot s} \cdot \Delta P_m^{f,set} \tag{3.10}$$

By converting the equation 3.10 from the frequency domain to the temporal domain, we obtain:

$$\Delta \dot{P}_m = \frac{\Delta P_m^{f,set} - \Delta P_m}{\tau_t} \tag{3.11}$$

Finally, by substituting the equation 3.5 of the control loop in the equation 3.11, we obtain the ordinary differential equation for the primary frequency control:

$$\Delta \dot{P}_m = \frac{-\frac{1}{S} \cdot \Delta f - \Delta P_m}{\tau_t} \tag{3.12}$$

Because of the integral nature of the controller, the turbine will apply the mechanical power deviation ΔP_m^{set} but with a delay. This delay is the consequence and is dependent to the time constant τ_t. Because of this delay, the mechanical power deviation really apply at time t isn't ΔP_m^{set} but it is ΔP_m.

On the other hand, the integral nature of the controller allows the turbine to reach effectively the given value ΔP_m^{set} in input.

From the equation 3.11 for the primary frequency control and the equation 2.38 for an uncontrolled power system, we obtain the system of equations relating to the power system with primary frequency control.

3.5 Stability

By adding the primary frequency control, the stability of the system frequency must be considered again. In this case, the frequency dynamics of the power system is always defined by ordinary differential equations. So, we can use the same theoretical tools as for the uncontrolled power system to demonstrate its stability.

The system of equations to consider is composed by the linearised equation 2.42 for the uncontrolled power system and by the equation 3.12 for the primary frequency control.

The linear state space system is:

$$\begin{cases} \dot{x} = \begin{pmatrix} -\frac{C}{D_l} & C \\ -\frac{1}{S\cdot\tau_t} & -\frac{1}{\tau_t} \end{pmatrix} \cdot x + \begin{pmatrix} -C \\ 0 \end{pmatrix} \cdot u \\ y = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \cdot x \end{cases} \tag{3.13}$$

where :

$$x = \begin{pmatrix} \Delta f \\ \Delta P_m \end{pmatrix} \tag{3.14}$$

$$u = \Delta P_{load} \tag{3.15}$$

$$C = \frac{f_0}{2\cdot H\cdot S_B + W_0} \tag{3.16}$$

By identifying the constant matrix A, the characteristic equation is defined by:

$$\begin{vmatrix} \lambda + \frac{C}{D_l} & -C \\ \frac{1}{S\cdot\tau_t} & \lambda + \frac{1}{\tau_t} \end{vmatrix} = 0 \tag{3.17}$$

The characteristic equation is the quadratic equation:

$$\lambda^2 + \lambda\cdot(\frac{C}{D_l} + \frac{1}{\tau_t}) + \frac{C}{\tau_t}\cdot(\frac{1}{D_l} + \frac{1}{S}) = 0 \tag{3.18}$$

The eigenvalues are roots of the characteristic equation. By identifying coefficients a, b, c as coefficients of the quadratic equation $a\cdot\lambda^2 + b\cdot\lambda + c = 0$, we know the roots are:

$$\lambda_1, \lambda_2 = \frac{-b\pm\sqrt{\Delta}}{2\cdot a} = \frac{-b\pm\sqrt{b^2 - 4\cdot a\cdot c}}{2\cdot a} \tag{3.19}$$

According to the theorem on the stability of a linear system in the subsection 2.5.1, we have to demonstrate the real part of all eigenvalues are strictly negative to proof the asymptotically stability.

Foremost, because parameters C, D_l, τ_t and S are always strictly positive, coefficients a, b and c are strictly positive:

$$a, b, c > 0 \tag{3.20}$$

From this observation and the equation 3.19, we have two cases to consider to ensure strictly negative eigenvalues according to the value of the discriminant Δ.

For the first one, we have a negative discriminant Δ. From the equation 3.20, the real part of eigenvalues are always strictly negative.

$$\forall \Delta \in \mathbb{R} : \Delta \leq 0 \Rightarrow Re(\lambda_1) = Re(\lambda_2) = \frac{-b}{2 \cdot a} < 0 \tag{3.21}$$

For the second one, we have a strictly positive discriminant. From the equation 3.20, the real part of the second eigenvalue λ_2 is always strictly negative.

$$\forall \Delta \in \mathbb{R} : \Delta > 0 \Rightarrow \begin{cases} Re(\lambda_1) = \frac{-b+\sqrt{\Delta}}{2 \cdot a} \\ Re(\lambda_2) = \frac{-b-\sqrt{\Delta}}{2 \cdot a} < 0 \end{cases} \tag{3.22}$$

The real part of the first eigenvalue λ_1 is strictly negative if and only if:

$$-b + \sqrt{\Delta} < 0 \tag{3.23}$$

We can resume these two cases by:

$$\forall \Delta \in \mathbb{R} : \Delta \leq 0 \cup (\Delta > 0 \cap -b + \sqrt{\Delta} < 0) \Rightarrow Re(\lambda_1), Re(\lambda_2) < 0 \tag{3.24}$$

The equation 3.23 can be rewritten:

$$-b + \sqrt{b^2 - 4 \cdot a \cdot c} < 0 \Leftrightarrow \sqrt{b^2 - 4 \cdot a \cdot c} < b \tag{3.25}$$

Because the two terms are strictly positive, we can raise each term to the power 2:

$$\sqrt{b^2 - 4 \cdot a \cdot c}^2 < b^2 \Leftrightarrow b^2 - 4 \cdot a \cdot c < b^2 \tag{3.26}$$

So, we can simplify the condition to:

$$-4 \cdot a \cdot c < 0 \tag{3.27}$$

According to the equation 3.20, the equation 3.27 is always true.

So, we can simplify the equation 3.24 by:

$$\forall \Delta \in \mathbb{R} : \Delta \leq 0 \cup \Delta > 0 \Rightarrow Re(\lambda_1), Re(\lambda_2) < 0 \tag{3.28}$$

However, we can note the condition $\Delta \leq 0 \cup \Delta > 0$ is always true. So, we prove eigenvalues for a power system with the primary frequency control have always a real part strictly negative. The system frequency is thus always asymptotically stable.

$$\forall \Delta \in \mathbb{R} : Re(\lambda_1), Re(\lambda_2) < 0 \tag{3.29}$$

3.6 Numerical simulation and results

With the ODE system we defined for the power system with primary frequency control, we can build a numerical simulation. To conduct this, we implement the ODE system in Matlab and solve it thanks to the function *ode45*. The source code is available in the appendix A.2.

In the same way as the numerical simulation for an uncontrolled power system in the section 2.6, we consider the disturbance as a step function. In practice, we arbitrarily define the nominal value of the mechanical power deviation ΔP_{m0}^{set} as equal to zero and the load power deviation ΔP_{load} as the disturbance. As for an uncontrolled power system, this choice does not matter because the main point is the global power deviation ΔP.

A difference appears for the global value of mechanical power deviation. Indeed, the control loop of the primary frequency control allows to adjust the mechanical power deviation $\Delta P_m^{f,set}$ depending on the system frequency deviation. It is this simple difference which slows down and finally stops the frequency drop.

In our model, we define values of parameters given in the table 3.1, based on [And11].

Parameter		Value	
The total inertia constant	H	5	$[s]$
The total rating	S_B	4000	$[MW]$
The nominal frequency	f_0	50	$[Hz]$
The frequency-dependency constant	D_L	$\frac{1}{80}$	$[\frac{Hz}{MW}]$
The nominal kinetic energy	W_0	100	$[\frac{MW}{Hz}]$
The global speed droop	S	$\frac{1}{2000}$	$[\frac{Hz}{MW}]$
The time constant of the turbine	τ_t	$\{0.1, 1, 2\}$	$[s]$

Table 3.1: Values of parameters for the numerical simulation of the primary frequency control, based on [And11]

We note the majority of parameters are identical to parameters of an uncontrolled power system. This is completely understandable while the primary frequency control is added to the uncontrolled power system. We are expanding parameters by the primary frequency control ones: the global speed droop characteristic S defining the control loop and the time constant τ_t of the turbine defining the turbine dynamics.

From UCTE definitions, the mechanical power deviation $\Delta P_m^{f,set}$ is equal to 0 for a frequency deviation included between -0.02 Hz and 0.02 Hz. Beyond these values, the mechanical power deviation $\Delta P_m^{f,set}$ decreases, respectively increases, linearly according to the speed droop characteristic. The minimal, respectively maximal, mechanical power deviation $\Delta P_m^{f,set}$ is reached for a frequency deviation of -0.2 Hz, respectively 0.2 Hz.

So, we need to be aware about the minimal, or maximal, mechanical power deviation $\Delta P_m^{f,set}$ for our numerical simulation. These boundaries depend on the frequency deviation for the full activation of the primary reserve and on the speed droop characteristic. In particular, while ΔP_{m0}^{set} equals 0, the wanted mechanical power deviation ΔP_m^{set} corresponds to $\Delta P_m^{f,set}$. This represents the available primary reserve. We have:

$$|\Delta P_{m,max}^{set}| = |\Delta P_{m,min}^{set}| = \frac{|\pm 0.2|}{S} = 400 \text{ MW} \tag{3.30}$$

3.6.1 The variation of the load power deviation

We can observe on the figure 3.8 theoretical responses of the power system with primary frequency control by setting the time constant of the turbine τ_t and by varying the load power deviation ΔP_{load}.

Foremost, we see the objective of the primary frequency control is reached : the frequency drop is damped and is finally stopped. The mechanical power deviation ΔP_m is of opposite sign to the frequency deviation Δf. Indeed, the mechanical power deviation ΔP_m varies to reduce the imbalance caused by the load power deviation ΔP_{load}.

If ΔP_{load} increases, i.e. the consumed power increases, ΔP_m are increasing to inject (generated) power in the grid through an upward regulation. Inversely, if ΔP_{load} decreases, i.e. the consumed power decreases, ΔP_m are decreasing to reduce (generated) power in the grid through a downward regulation.

Because the imbalance is reduced, the system frequency becomes more stable. Indeed, remind the system frequency deviation occurs due to an imbalance between the consumed power and the generated power. We can thus see a stabilization in the system frequency, i.e. the frequency deviation Δf converges, when the mechanical power deviation ΔP_m cancels the load power deviation ΔP_{load}.

The upper plot shows an over-damping when the load power deviation ΔP_{load} is close to

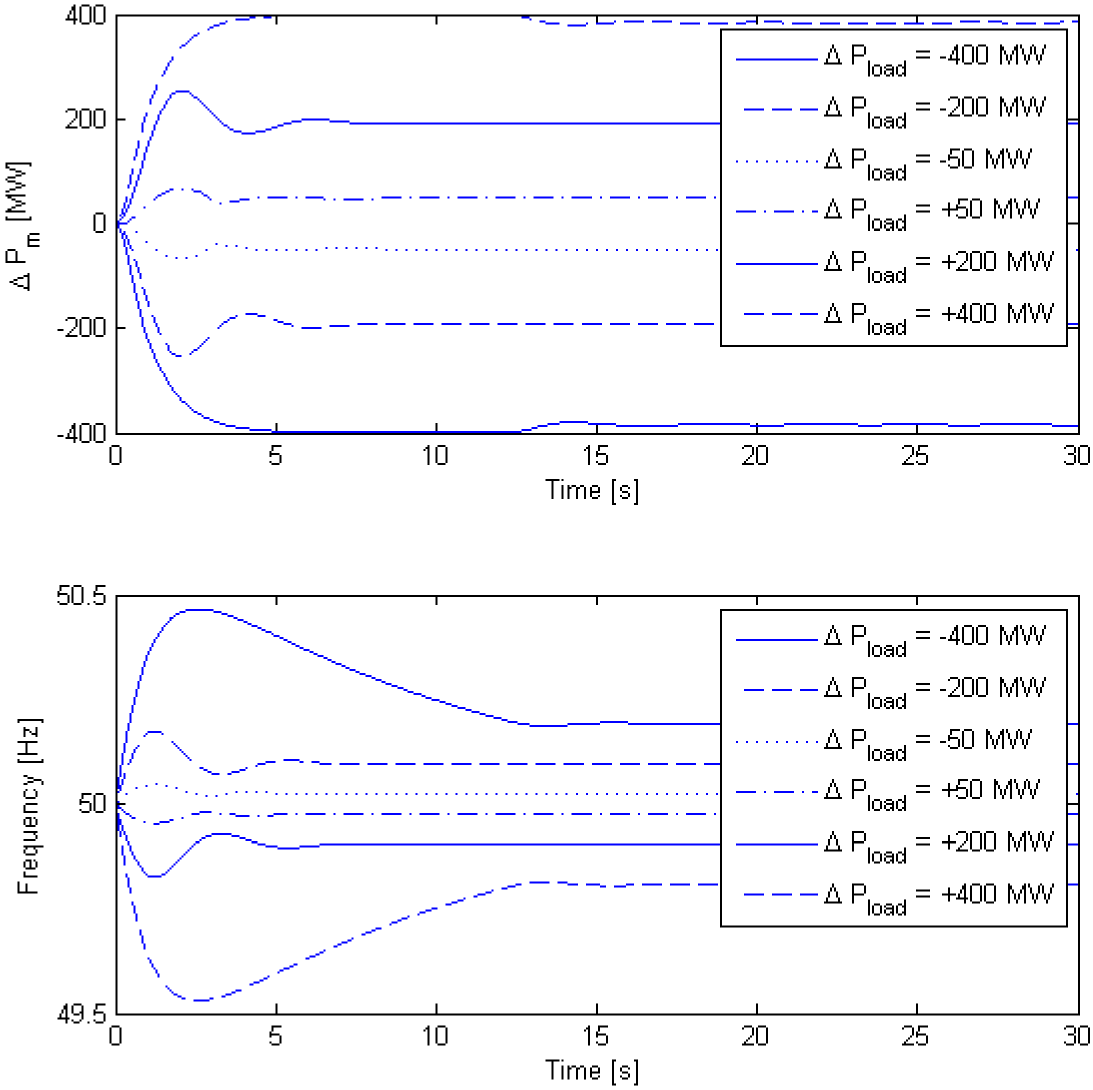

Figure 3.8: Theoretical responses of the power system with primary frequency control, comparison on ΔP_{load} with $\tau_t = 1$ s

the available primary reserve. However, there is else an under-damping with a presence of oscillations before the stabilization.

The lower plot shows an under-damping with a presence of oscillations before the stabilization, whatever the value of the load power deviation ΔP_{load}. However, if the ΔP_{load} is close to the available primary reserve, we can see the dynamic frequency is more important but there is less oscillations.

3.6.2 The variation of the time constant of the turbine

Then, we can observe on figures 3.9 and 3.10 the theoretical responses of the power system with primary frequency control by setting the load power deviation ΔP_{load} and by varying the time constant of the turbine τ_t. Note we represent only results for an upward regulation, results for a downward regulation follow the same logic as show with the figure 3.8.

In the first figure, we choose a ΔP_{load} equals to the maximal mechanical power deviation.

Whatever the mechanical power deviation ΔP_m or the system frequency f, if the time constant of the turbine τ_t is small enough, we can observe an over-damping. With a greater τ_t, we have an under-damping without any oscillation. In this last case, we note a high dynamic frequency which, for a τ_t equals to 2 seconds, is close to the maximum dynamic frequency defining by UCTE, i.e. a frequency deviation Δf equals to 0.8 Hz.

Moreover, we observe the mechanical power deviation ΔP_m does not change significantly with the time constant τ_t, while the dynamic frequency changes significantly. This seems quite normal because ΔP_m converges quickly to its maximum.

In the second figure, we choose a ΔP_{load} below the maximal mechanical power deviation.

As for the first figure, a τ_t small enough leads to a over-damping of the system frequency f. However, as opposed of the first figure, a greater τ_t leads to an under-damping with a presence of oscillations, and the dynamic frequency is proportionally lower.

With a time constant τ_t relatively too high, we note the mechanical power required is much greater than necessary to a smaller value of τ_t. Resulting from this, the dynamic frequency increases with the value of τ_t.

In both figures, we see the system frequency deviation Δf is finally identically whatever the value of the time constant τ_t.

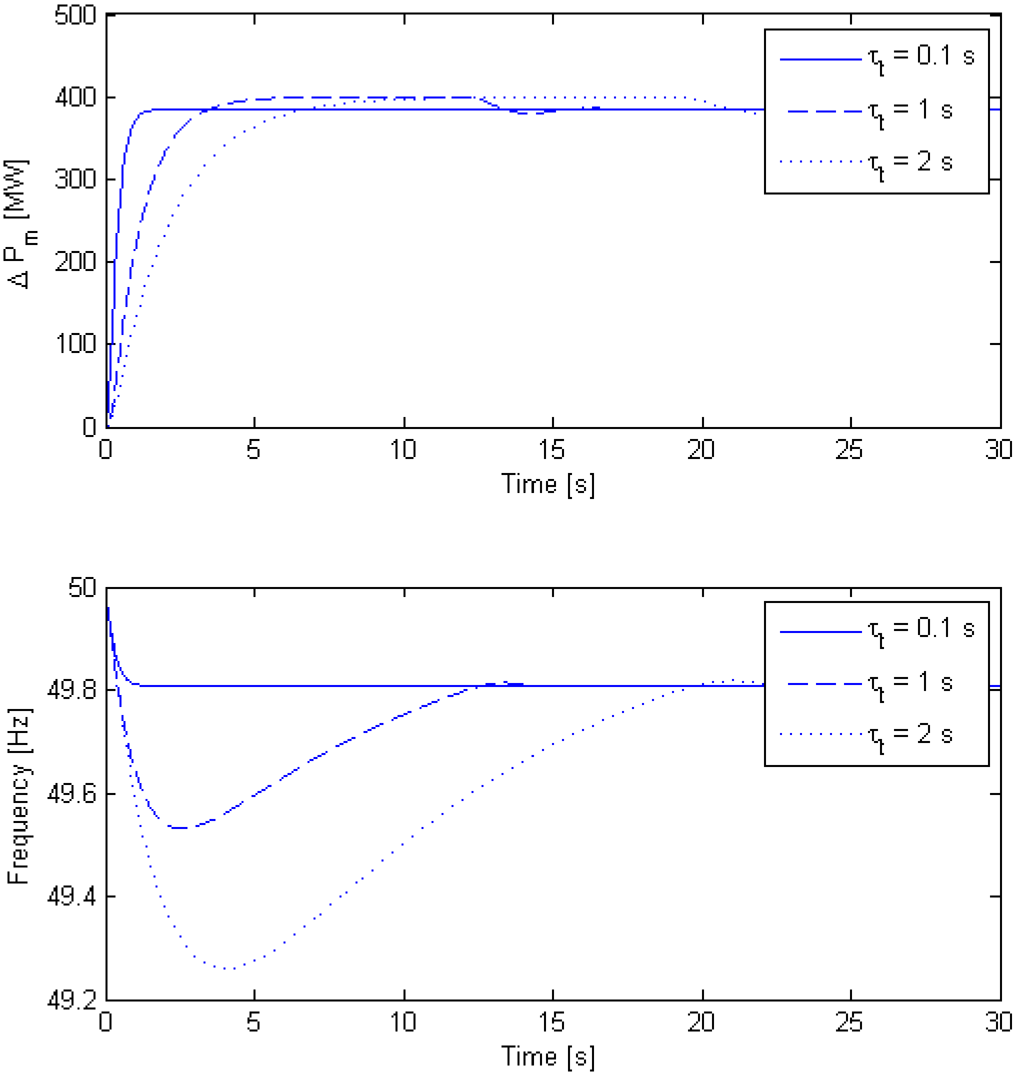

Figure 3.9: Theoretical responses of the power system with primary frequency control, comparison on τ_t with $\Delta P_{load} = +400$ MW

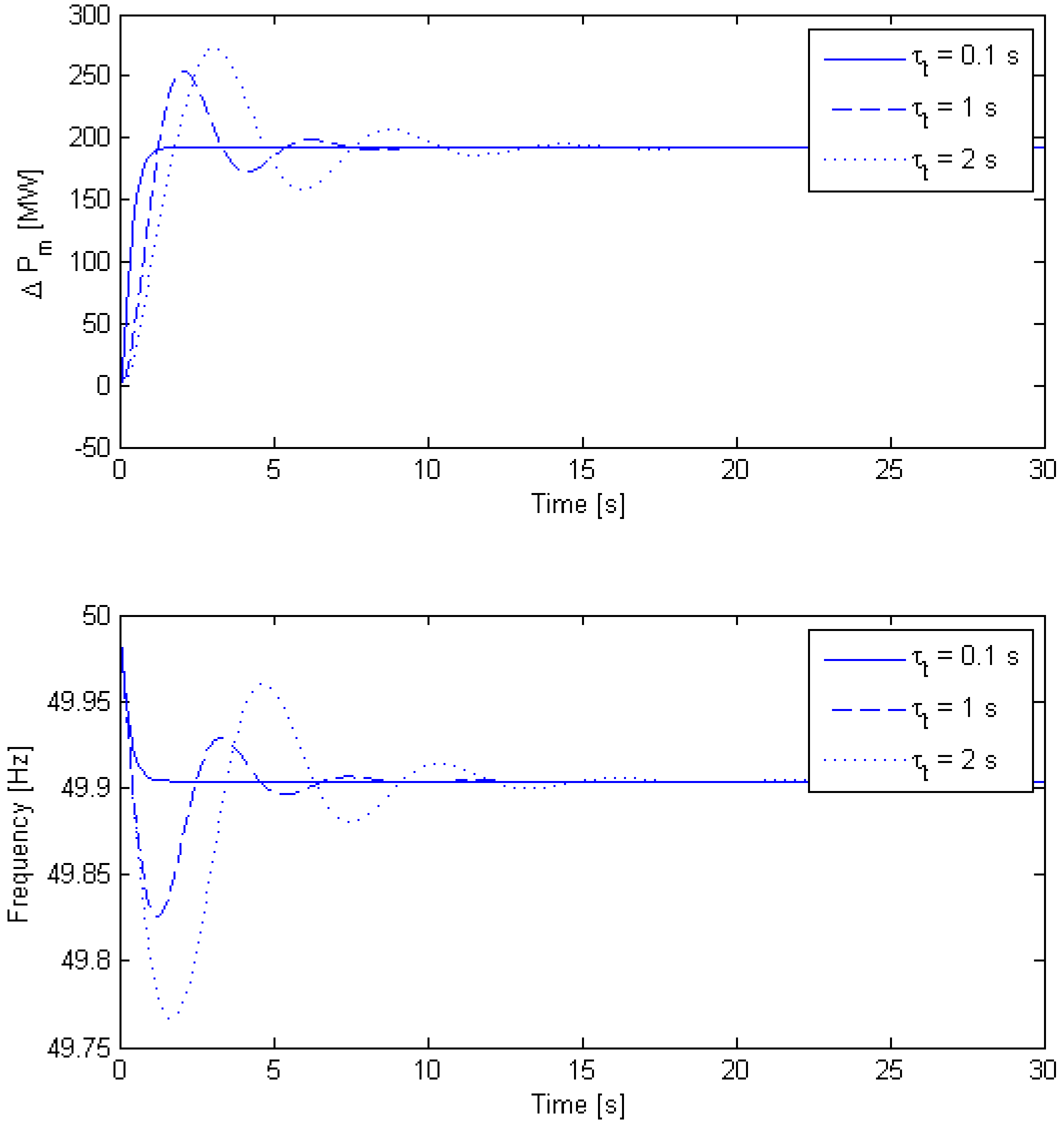

Figure 3.10: Theoretical responses of the power system with primary frequency control, comparison on τ_t with $\Delta P_{load} = +200$ MW

3.6.3 Conclusion

Results show us a power system with primary frequency control can be mainly characterized by two parameters.

The time constant of the turbine controller τ_t defines the activation speed of the primary reserve. While the power imbalance is close to the available primary reserve, τ_t mainly defines the dynamic frequency, i.e. a great τ_t defines a high dynamic frequency and inversely; else, τ_t defines oscillations in the system frequency and in the mechanical power deviation, i.e. a great τ_t defines more oscillations.

It is thus interesting to have a small τ_t. However, the time constant is linked to the intrinsic feature of the turbine : a turbine can't generate instantaneously the required power.

The speed droop characteristic S defines the available primary reserve. However, there are two points to remember : the first one is the primary reserve is defined and fixed by UCTE, and the second one is the speed droop characteristic is inherent of the turbine dynamics.

Finally, we conclude the primary frequency control meets its objective by damping the frequency drop. In practice, this is the case for many years. However, we feel the performance of primary frequency control is limited by its own implementation to adjust the generated power through the mechanical power. Indeed, the modulation of the generated power, and so the activation of the primary reserve, is limited by parameters inherent in the turbine.

In a context where the concept of smart grid is emerging, where a certain awareness appears at the consumer level and where renewable energy sources leads to volatility, new ways of approaching the problem of the frequency regulation are becoming necessary. A possibility is to adjust the consumed power rather than the generated power through the mechanical power, as the well know demand-side management or a power management of loads introduced in the chapter 4.

Chapter 4

Power system with power management of loads

In the chapter 3, we explained how primary frequency control, through the modulation of the mechanical power of generators, works. Through a numerical simulation and results, we concluded the primary frequency control achieves its objective.

In a context where ancillary services are more and more necessary, a legitimate question is: is there another approach to provide a primary frequency regulation?

A possible answer would be to modulate the consumed power rather than the generated power. The prime choice to modulate the generated power has a sense in a context where the consumed power is too difficult to manage. Today, the number of mobile devices containing a battery are increasing in a tremendous way. In a relatively near future, we can also imagine electric vehicles as "mobile devices" or an added battery to a solar panel system profiting to the presence of a power inverter[1].

The idea to modulate the consumed power is not new. We can cite the Demand-Side Management which aims to reduce the global consumed power through the demand rather than the supply. A problem of this simple concept is that we need to allow a frequency regulation by the modulation of the consumed power. In our case, the frequency regulation is made possible because we shift the demand through the consumed power at another time. It is important to understand we don't provide an energy saving a priori, but we don't need to generate energy.

To allow us to modulate the consumed power, we can take advantage of the smart grid concept. With a smarter approach, we can imagine to provide a modulation of the consumed power by a better management of this power. In our case, we choose to introduce a

[1] A power inverter is an electrical device which transforms a direct current to an alternating current. This interest comes from solar panels which provide a direct current.

so-called power management of loads.

In this chapter, we introduce the concept of power management of loads by: (1) *a simple model of a power system with power management of loads ;* (2) *a dynamic description of mechanisms for the power management of loads ;* (3) *a description about the stability of a linear time-delay system and a development of tools to ensure the theoretical stability of the system ;* (4) *a presentation of results collected by a numerical simulation of the model.*

4.1 A model

The power management of loads is inserted as a loop to the uncontrolled power system. As primary frequency control, its role is to act as a controller in the power system thanks a feedback: the objective is the same. However, the power management of loads don't adjust the mechanical power but a part of the load power. The figure 4.1 gives the block-diagram of the power system with power management of loads.

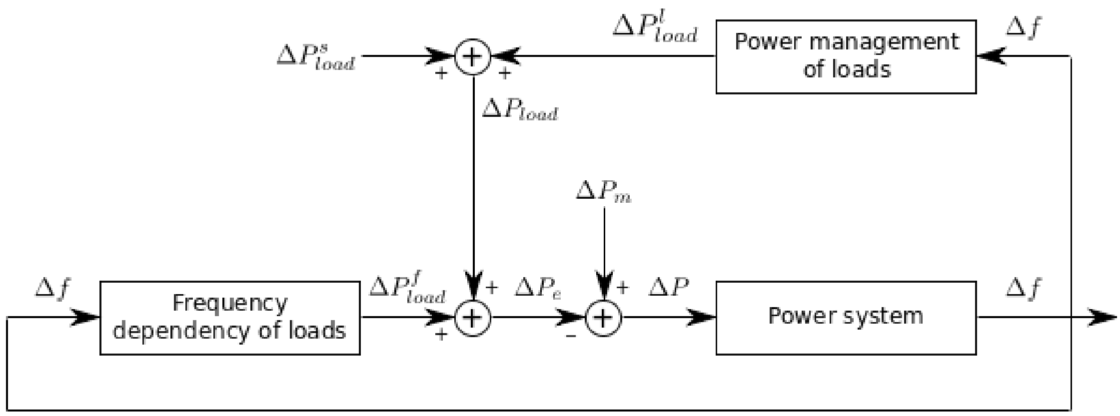

Figure 4.1: Block diagram of a power system with the power management of loads

We see the system has two inputs, the load power deviation which can't be managed ΔP^s_{load} and the mechanical power deviation ΔP_m, and one output, the frequency deviation Δf.

The power management of loads takes the frequency deviation Δf as an input and the load power deviation which can be managed ΔP^l_{load} as an output. In other words, the power management of loads consists to change the load power deviation ΔP_{load} through a manageable part ΔP^l_{load} from the frequency deviation Δf to reduce and stop the frequency drop.

The block-diagram of the power management of loads is given in the figure 4.2. We see it can be decomposed in three parts: the allocation function, the quantized load and a time-delay.

Figure 4.2: Block diagram of the power management of loads

The allocation function determines the number of loads n to switch off according to the frequency deviation Δf. We suppose the number of loads is automatically adjusted at any moment. To know the load power deviation $\Delta P_{load}^{l,set}$ we want to apply to the power system, we assume and consider theoretically each load as a quantized load. However, there exists a propagation delay between the order sent to load and the execution of the order. So, we have to consider a time-delay : for a certain instant, the applied load power deviation ΔP_{load}^{l} is not exactly the same than the wanted load power deviation $\Delta P_{load}^{f,set}$.

4.2 The power management of loads

The power management of loads aims to regulate the frequency in the grid by varying the consumed power. In this master thesis, we take in consideration a mobile device, or more generally a load, could switch off or switch on according to an order. In this case, an amount of loads allow us to decrease the consumed power by switching off a certain number of mobile devices.

We don't consider the consumption of loads as the possibility to increase the consumed power by switching them on. This choice comes from the nature of a mobile device: in practice, we don't connect a mobile device to the grid while it is in an use on battery. In the same way, we don't consider loads which can directly inject power in the grid because a current mobile device doesn't. However, the reasoning is typically the same for the downward regulation.
Decrease the consumed power is equivalent to increase the generated power, and so to inject power in the grid. Therefore, we have only an upward regulation by our power management of loads.

4.2.1 The time-delay

In our model, we choose to determine a number of loads which will affect the imbalance on the grid. To implement this choice in practice, we consider a centralized IT platform which is managing all loads connected to it. With this consideration, we introduce the necessity to communicate from the IT platform and each load scattered on a relatively large area. So, we have to consider a propagation delay as a pure delay between the order sent to load and the execution of the order.

The propagation delay depends on the distance between the IT platform and the load, on the data to send and the protocol to apply, but also on the physical channel whatever its inherent features or the context of its use as a congestion. The propagation delay will change for each load and at any moment.

To simplify the model without neglecting a propagation delay, we assume the propagation delay, so-called τ, is the same for all loads and is constant over time. Mathematically, we write:

$$\Delta P^{l}_{load}(t) = \Delta P^{l,set}_{load}(t - \tau) \tag{4.1}$$

By the introduction of a pure delay, our system, which was composed by ordinary differential equations, contains now a delay differential equation. So, we have to consider a *time-delay system*. In other words, the response of the power management of loads will be late from a delay time τ. Intuitively, the stability and the stabilization of a time-delay system is thus more complex than an ordinary system.

4.2.2 The quantized load

The concept of a load may be difficult to quantify a priori. In practice, we have to cope with the scattering of loads on a large area and with the quality and the quantity of loads. For example, perform accurate measurements of each available load or forecast the consumption of an electric device in a near future are not easy tasks. Moreover, nothing specifies the loads are identical.

To simplify the model, we consider a quantized load p which corresponds to a basic load. We assume each indivisible load in our portfolio can be consider as multiple of this quantized load.

By this way, we can determine the load power deviation which we want to apply:

$$\Delta P^{l,set}_{load}(t) = -p \cdot n(t) \tag{4.2}$$

The minus sign means we remove n quantized loads of the power system. If we remove these loads, we reduce the consumed power. That is what we want.

By substituting the equation 4.2 in the equation 4.1, we obtain:

$$\Delta P^{l}_{load}(t) = -p \cdot n(t - \tau) \tag{4.3}$$

4.2.3 The allocation function

The allocation function defines a number of quantized loads n to switch off from the frequency deviation Δf. Before to define the shape of this function, we have to explicit some constraints to respect the objective of an upward frequency regulation.

Constraints on the allocation function

Let be $N(t)$ the number of available quantized loads at time t.

The first constraint determines a lower and an upper boundaries for the number of quantized loads n defined by the allocation function. Trivially, the number of loads n must be positive and lower than the number of available loads at any time.

$$\forall t \in \mathbb{R}^+ : 0 \leqslant n(t) \leqslant N(t) \tag{4.4}$$

The second one allows to ensure an upward regulation. Indeed, we can switch off a number of quantized loads n only if we have to reduce the consumed power, i.e. if the system frequency f decreases. So, we have a positive number of quantized loads n for a strictly negative frequency deviation Δf.

$$\forall t \in \mathbb{R}^+ : \Delta f(t) < 0 \Rightarrow n(t) \geqslant 0 \tag{4.5}$$

The third one allows to forbid a downward regulation. Because we consider n as the number of quantized loads to switch off, a strictly positive n will worse the situation: if the system frequency f is upper than its nominal value and if we reduce the consumed power, the system frequency f will increase more.

$$\forall t \in \mathbb{R}^+ : \Delta f(t) \geqslant 0 \Rightarrow n(t) = 0 \tag{4.6}$$

If the frequency deviation Δf is equal to 0, the number of quantized loads n must be equal to 0 too. If the system frequency is equal to its nominal value, it is trivial.

The shape of the allocation function

According to constraint equations 4.4, 4.5 and 4.6, the allocation function must be a piecewise-defined function. This function is not necessary continuous.

Let be $D(\Delta f)$ as a function of the frequency deviation, and Δf_{min} as a frequency deviation from which all quantized loads switch off. We can write:

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ D(\Delta f(t)) & if \quad \Delta f_{min} < \Delta f(t) < 0 \\ N(t) & if \quad \Delta f(t) \leqslant \Delta f_{min} \end{cases} \tag{4.7}$$

The first piece defines the non-application of the power management of loads, i.e. while we are in the downward regulation. The second and third ones define the allocation function while we are in the upward regulation. We arbitrarily choose to define a third piece which defines a full activation of the load reserve. This piece is reached when the frequency deviation Δf is equal to or lower than a frequency deviation Δf_{min}.

The variation over time of the number of available quantized loads $N(t)$ could be problematic. In practice, we don't accurately forecast the value of the number of available quantized loads $N(t)$. That could be a problem if we have to forecast it ahead. We think it is thus more realistic to consider a minimal threshold.

So, we assume to choose a minimal number of available loads N_0:

$$\forall t \in \mathbb{R}^+, \exists N_0 \in \mathbb{N}^+ : N_0 \leqslant N(t) \tag{4.8}$$

We can rewrite the shape of the allocation function 4.7:

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ D(\Delta f(t)) & if \quad \Delta f_{min} < \Delta f(t) < 0 \\ N_0 & if \quad \Delta f(t) \leqslant \Delta f_{min} \end{cases} \tag{4.9}$$

To define the shape of the allocation function through the function $D(\Delta f)$, we have to consider the stability and the stabilization of the system frequency in the power system. These considerations are introduced in the section 4.3. Yet, let's set possible shapes.

The allocation function as a step function

In a first approach, we consider a bang-bang control : it is all or nothing. If the frequency deviation Δf is positive, i.e. if there is a downward regulation, the number of quantized loads n is equal to zero. Conversely, if the frequency deviation Δf is strictly negative, i.e. if there is an upward regulation, we are switching off all available quantized loads N_0.

Mathematically, we write the allocation function as :

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ N_0 & if \quad \Delta f(t) < 0 \end{cases} \tag{4.10}$$

The figure 4.3 gives an example of a allocation function as a step function.

Intuitively, a bang-bang control will lead to instability of the system frequency.

We first note the load power deviation ΔP^s_{load} is not directly measurable. We have to balance power in the system by knowing only the frequency deviation Δf. In second, we note the bang-bang control will switch off all available quantized loads N_0 for any negative

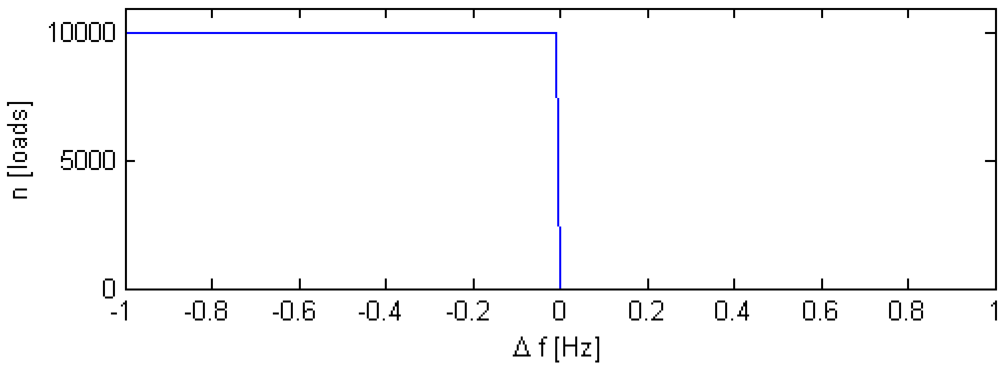

Figure 4.3: Example of a allocation function as a step function with $N_0 = 10^4$ loads

frequency deviation Δf, even for a very small.

So, if the power of all available quantized loads N_0 is bigger than the load power deviation ΔP^s_{load}, we imbalance more the power system if the frequency deviation Δf should be negative with a small absolute value. A bang-bang control is not a priori a good allocation function for a stable system, particularly associated to a time-delay system.

The allocation function as a P-controller

In a second approach, we have to consider the relevant problem of the allocation function as a step function. Because we have seen how the primary frequency control works, an idea may be to define a allocation function as a P-controller for the piece whose the value is not determined. By this way, we are actually simulating a speed droop characteristic which has more freedom of choice in its value.

By definition of a P-controller, we obtain the followed allocation function:

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ k_p \cdot \Delta f(t) & if \quad \Delta f_{min} < \Delta f(t) < 0 \\ N_0 & if \quad \Delta f(t) \leqslant \Delta f_{min} \end{cases} \tag{4.11}$$

By imposing a continuity between each piece, we can define the proportional gain k_p as:

$$k_p = \frac{N_0}{\Delta f_{min}} \tag{4.12}$$

The choice of a constant number of available quantized loads N_0 is assumed more here, because others problems could be considered.

By considering a non-constant $N(t)$, the number of switching off loads for a given frequency deviation Δf will change over time. If the number of available quantized loads $N(t)$ is too great, we could be in the same problem than the bang-bang control: the power of switching off loads could be too large compared to the load power deviation ΔP^s_{load}. If the number of available quantized loads $N(t)$ is too small, the impact of the power management on the system frequency f could be insignificant: switch off just a little more loads, which are available, could be sufficient to stop the frequency drop and to lead to a stabilization of the system frequency f.

Then, keeping a constant proportional gain allows us to know the behaviour of our power management of loads according to a frequency deviation Δf as a turbine has a fixed speed droop characteristic S.

By substituting the equation 4.12 in the equation 4.11, we have:

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ \frac{N_0}{\Delta f_{min}} \cdot \Delta f(t) & if \quad \Delta f_{min} < \Delta f(t) < 0 \\ N_0 & if \quad \Delta f(t) \leqslant \Delta f_{min} \end{cases} \tag{4.13}$$

The figure 4.4 gives an example of a allocation function as a P-controller.

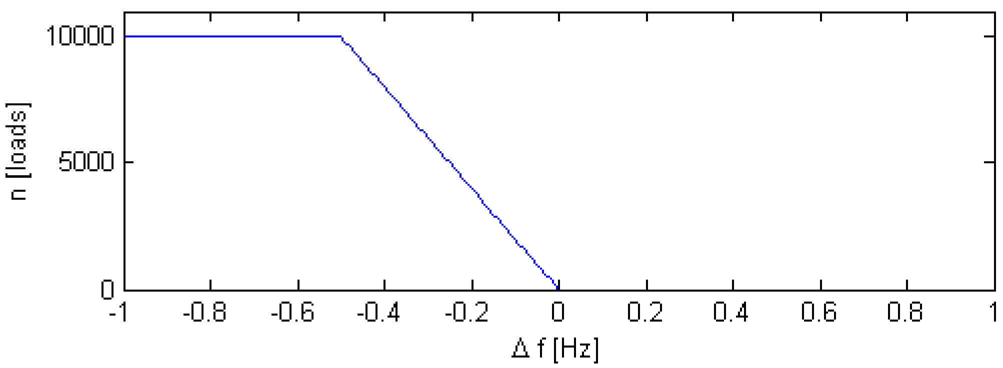

Figure 4.4: Example of a allocation function as a P-controller with $N_0 = 10^4$ loads and $\Delta f_{min} = -0.5$ Hz

We note the allocation function as a step function, i.e. the bang-bang control, is an extreme case of the allocation function as a P-controller:

$$\Delta f_{min} = 0 \tag{4.14}$$

In a such way, the second piece of the allocation function is never reached because it goes from the first piece to the third without going through the second.

We also note the P-controller allows to make a primary frequency regulation: as for the primary frequency control, the proportional nature of the controller ensure to have a static-error and so a steady-state.

The allocation function as a PD-controller

Because the stability and the stabilization of the system frequency is one of our main concerns, it may be interesting to consider a more stable controller by adding a derivative component. So, we could consider the allocation function as a PD-controller.

By definition of a PD-controller, we obtain the followed allocation function:

$$\forall t \in \mathbb{R}^+ : n(t) = \begin{cases} 0 & if \quad \Delta f(t) \geqslant 0 \\ k_p \cdot \Delta f(t) + k_d \cdot \Delta \dot{f}(t) & if \quad \Delta f_{min} < \Delta f(t) < 0 \\ N_0 & if \quad \Delta f(t) \leqslant \Delta f_{min} \end{cases} \tag{4.15}$$

Nevertheless, the allocation function as a PD-controller is a more complex shape and leads to some difficulties.

The first one is to maintain the continuity of our piecewise-defined function by considering a constant frequency deviation Δf_{min}. Indeed, to ensure the continuity we have to consider a frequency deviation Δf_{min} which is dependent of the derivative of the frequency deviation $\Delta \dot{f}(t)$.

The second one is to have a time-delay after to consider the derivative value of the error, which is the frequency deviation Δf here. This leads to consider a system with a derivative of the system frequency Δf at time t but also at time $t - \tau$. Although the writing is simple, the implementation and the numerical simulation or a analytical study of a such time-delay system are very more complex.

In the context of this master thesis, we assume to consider a allocation function as a P-controller by its parallel to the primary frequency control, but also by not needlessly complicating the first study of the subject.

4.3 Stability

Intuitively, a power system with power management of loads is not necessary asymptotically stable. In contrast to a power system with primary frequency control which can be set within the limits inherent to physical mechanisms, the definition of the allocation function allows us to a large flexibility on the behaviour of the power management of loads. The bang-bang control is an extreme example.

Nevertheless, we have to deal with a time-delay system, not an ordinary system. We can no longer use the same theoretical methods to determine the stability of the system.

4.3.1 Theoretical review: stability of a linear time-delay system

The stability concepts of a time-delay system is complex, not about existing methods itself but about the complexity of the theoretical analysis. From [WHS10], we can mention the two domains of methods : the time-domain and the frequency-domain.

In the time-domain, methods are based on the Lyapunov-Krasovskii stability theorem or the Razumikhin theorem. To can prove the stability of a time-delay system, we need to construct a Lyapunov-Krasovskii functional or a Lyapunov function. It is clearly not an easy task.

In the frequency-domain, the method is similar to the approach to analyse the stability of a linear ordinary system through the characteristic equation of the system. That why we choose the characteristic equation's method, allowing us to consider the stability for a linear time-delay system.

From [WHS10], we define a linear time-delay system as:

$$\begin{cases} \dot{x}(t) = A \cdot x(t) + A_d \cdot x(t-h) \\ x(t) = \phi(t), t \in [-h, 0] \end{cases} \tag{4.16}$$

Where $x(t)$ is the state vector, h is a strictly positive delay, $\phi(t)$ is the initial condition and, A and A_d are constant system matrices.

From [WHS10] and [Sch95], we know a necessary and sufficient condition for the stability of a linear time-delay system.

Theorem Stability of a linear time-delay system.
The system 4.16 is asymptotically stable if and only if all the roots λ of its characteristic function

$$\det(\lambda \cdot I - A - A_d \cdot e^{-h \cdot \lambda}) = 0 \tag{4.17}$$

have negative real parts.

We note the equation 4.17 is a transcendental equation which is difficult to solve analytically.

4.3.2 Stability of a power system with power management of loads

The linear time-delay system to considered is composed by the linear equation 2.42 for the uncontrolled power system to which we add the equation 4.3 for the power management of loads. By substituting the second in the first and by considering the unmanageable part of the load power, we have the linear equation:

$$\Delta \dot{f}(t) = \frac{f_0}{(2 \cdot H \cdot S_B + W_0)} \cdot \left(\Delta P_m(t) - (\Delta P^s_{load}(t) - p \cdot n(t - \tau)) - \frac{1}{D_l} \cdot \Delta f(t) \right) \quad (4.18)$$

We study the stability of a power system with power management of loads whose the allocation function is a P-controller. So, we consider the number of quantized loads n is defined by the equation 4.13.

The stability through the characteristic equation

Because the allocation function is a piecewise-defined function composed by three pieces, we have to consider three cases.

In the first one, the allocation function is null. By substituting $n(t-\tau) = 0$ in the equation 4.18, the system is not any more a time-delay system and has exactly the same shape as for an uncontrolled power system. According to the chapter 2, we know a such system is always asymptotically stable.

In the third one, the allocation function is a constant and the reasoning can be similar. By substituting $n(t - \tau) = N_0$ in the equation 4.18, the system is not any more a time-delay system and has the same shape as for an uncontrolled power system with an additional term. However, this term is not influencing the system matrix A of the system. So, results on the stability of the system are the same: the system is always asymptotically stable.

In the second one, the allocation function is not constant. So, the system is well a time-delay system for all $\Delta f \in \mathbb{R}, \Delta f_{min} \leq \Delta f < 0$. We have:

$$\Delta \dot{f}(t) = \frac{f_0}{(2 \cdot H \cdot S_B + W_0)} \cdot \left(\Delta P_m(t) - \Delta P^s_{load}(t) + p \cdot \frac{N_0}{\Delta f_{min}} \cdot \Delta f(t - \tau) - \frac{1}{D_l} \cdot \Delta f(t) \right) \quad (4.19)$$

By rewriting the equation 4.19 in a linear time-delay system as 4.16, we obtain the equation:

$$\dot{x}(t) = -\frac{C}{D_l} \cdot x(t) + C \cdot p \cdot \frac{N_0}{\Delta f_{min}} \cdot x(t - h) \quad (4.20)$$

where:

$$
\begin{aligned}
x(t) &= \Delta f(t) && (4.21)\\
u(t) &= \Delta P_m(t) - \Delta P^s_{load}(t) && (4.22)\\
h &= \tau && (4.23)\\
C &= \frac{f_0}{2 \cdot H \cdot S_B + W_0} && (4.24)
\end{aligned}
$$

By identifying system matrices A and A_d in the equation 4.20, the characteristic equation 4.17 can be defined as:

$$\lambda + \frac{C}{D_l} - C \cdot p \cdot \frac{N_0}{\Delta f_{min}} \cdot e^{-\tau \cdot \lambda} = 0 \tag{4.25}$$

Referring to the theorem in the subsection 4.3.1, we have to demonstrate the real part of all eigenvalues, i.e. all roots of this characteristic equation, is strictly negative to prove the system is asymptotically stable.

We have to keep in mind the asymptotic stability is here piecewise-defined as the allocation function. So, this stability is not concerned and ensured if the frequency deviation Δf changes in a such way that the allocation function continuously alternates from one piece to another one. The bang-bang control is a good example. So, this approach is correct to some extent, i.e. if there is not a continuous alternating among pieces. Intuitively, for a larger second piece, i.e. a lower frequency deviation Δf_{min}, the alternating of pieces is less problematic.

Numerical solving

The characteristic equation 4.25 is a transcendental equation whose the analytical solving is beyond the purpose and the scope of this master thesis. So, we have to solve it numerically. Because of the complexity of a transcendental equation, especially the difficulty to accurately determine the number of roots, we consider only one root of the transcendental equation in our approach. We will see results are confirmed during the numerical simulation in the section 4.4.

The presence of parameters requires to test the stability of the system for an interval of values for some relevant parameters to study. Here, the objective is to prove the power system with power management of loads can be arbitrarily led to an asymptotically stability. In the following, we give numerical tools to check the asymptotic stability of the system according the chosen parameters.

Our interest is mainly focused on parameters introduced by the power management of loads: the quantized load q, the frequency deviation Δf_{min} for full activation, the threshold for the number of available quantized loads N_0 and the time-delay τ. Parameters inherent to the uncontrolled system doesn't directly control the behaviour of the power management of loads.

Among the four parameters, we are considering only two as relevant parameters. Indeed, we can roughly resume the behaviour by the delay between the order and its execution, and the proportional gain which determines the load power deviation to apply. The first one is represented by the time-delay τ. The second one is represented by the quantized load q, the frequency deviation Δf_{min} and the number of available quantized loads N_0.

This distinction can be noted in the characteristic equation 4.25: the time-delay appears in the exponent of the exponential while the three others parameters appears in the coefficient. The variation of one of these three parameters has thus its equivalent by the variation of one of the two remaining parameters.

We choose to fix the frequency deviation Δf_{min} for full activation as the same value of the frequency deviation for full activation of the primary reserve defined by the UCTE within the primary frequency control.

$$\Delta f_{min} = 0.2 \text{ Hz} \tag{4.26}$$

For the quantized load q, we consider the current power consumption of a laptop.

$$q = 50 \text{ W} \tag{4.27}$$

The value of fixed parameters are resumed in the table 4.1.

Parameter		Value	
The total inertia constant	H	5	$[s]$
The total rating	S_B	4000	$[MW]$
The nominal frequency	f_0	50	$[Hz]$
The frequency-dependency constant	D_L	$\frac{1}{80}$	$[\frac{Hz}{MW}]$
The nominal kinetic energy	W_0	100	$[\frac{MW}{Hz}]$
The frequency deviation for full activation	Δf_{min}	0.2	$[Hz]$
The quantized load	q	50	$[W]$

Table 4.1: Values of fixed parameters for the numerical solving of the characteristic equation

Our methodology is to fix one relevant parameter and to solve numerically the characteristic equation 4.25 by considering some test values for the other relevant parameter. If and only if the real part of the eigenvalue is strictly negative, i.e. the real part of the root of the characteristic equation, we know the power system is asymptotically stable. By this way, we can determine test values, or prove their non-existence, which leads to the asymptotic stability of the system.

We choose to implement this methodology in Matlab thanks to the function *fsolve*. The source code is given in the appendix A.3.1. Note the numerical solving is based on the characteristic equation 4.25 which is determined from the linearised time-delay system 4.18.

Results

We introduce results through two examples. For each one, we have a fixed value for one relevant parameter and a set of test values for the other relevant parameter. We choose to define an interval of test values with a constant step between both consecutive values. Our Matlab function returns us test values which leads to the asymptotic stability, so-called stable values. We do that for some fixed values.

In the first one, we fix the number of available quantized loads N_0. Results are given in the table 4.2. We observe the stability of the system is inversely proportional to the number of available quantized loads N_0.

Intuitively, this statement is coherent. For a same frequency deviation Δf, the load power deviation ΔP_{load}^{l} from the power management of loads is more important for a greater number of available quantized loads N_0. So, it is more likely the imbalance between the generated power and the consumed power is reversed. Therefore, we will switch off more available quantized loads as necessary and will create a new imbalance which can lead to instability.

It is the same reasoning as for the bang-bang control introduced in the subsection 4.2.3. According to the coefficient of the exponential in the equation 4.25, increase the number of available quantized loads N_0 is equivalent to decrease the frequency deviation Δf_{min}. So, we tend to a bang-bang control.

Fixed value $[loads]$	Test values $[Hz]$	Test step $[Hz]$	Stable values $[Hz]$
$N_0 = 10^5$	$\tau \in [0.1; 15]$	0.1	$\tau \in [0.1; 15]$
$N_0 = 10^6$	$\tau \in [0.1; 15]$	0.1	$\tau \in [0.1; 15]$
$N_0 = 10^7$	$\tau \in [0.1; 15]$	0.1	$\tau \in [0.1; 0.5]$
$N_0 = 10^8$	$\tau \in [0.1; 15]$	0.1	$\tau \in \emptyset$

Table 4.2: Results about the system stability with a fixed N_0 by testing τ

In the second one, we fix the time-delay τ. Results are given in the table 4.3. We observe the stability of the system is inversely proportional to the time-delay τ.

Intuitively, this statement is coherent. For a same frequency deviation Δf, we will act with further delay to counter the imbalance in the power system. So, the frequency deviation Δf increases longer and will be greater before the compensation to reduce the imbalance. Because we have a time-delay system, this greater frequency deviation Δf leads to switch off more available quantized loads for a same imbalance. Therefore, it is more likely the delay leads to switch off more loads than necessary.

Fixed value $[loads]$	Test values $[Hz]$	Test step $[Hz]$	Stable values $[Hz]$
$\tau = 0.1$	$N_0 \in [10^5; 10^8]$	10^5	$N_0 \in [10^5; 5.05 \cdot 10^7]$
$\tau = 0.5$	$N_0 \in [10^5; 10^8]$	10^5	$N_0 \in [10^5; 1.02 \cdot 10^7]$
$\tau = 1.0$	$N_0 \in [10^5; 10^8]$	10^5	$N_0 \in [10^5; 5.20 \cdot 10^6]$
$\tau = 2.0$	$N_0 \in [10^5; 10^8]$	10^5	$N_0 \in [10^5; 2.07 \cdot 10^6]$

Table 4.3: Results about the system stability with a fixed τ by testing N_0

4.4 Numerical simulation and results

With the DDE system we defined for the power system with power management of loads, we can build a numerical simulation. To conduct this, we implement the DDE system in Matlab and solve it thanks to the function *dde23*. The source code is available in the appendix A.3.2.

The reader have to keep in mind we choose to implement the non-linear time-delay system despite the linearisation of the system to demonstrate its asymptotic stability. In practice, we note these boundaries of instability stay close.

In the same way as previous numerical simulations, we consider the disturbance as a step function. In practice, we arbitrarily define the mechanical power deviation ΔP_m as equal to zero and the load power deviation ΔP^s_{load} as the disturbance. As for an uncontrolled power system, this choice does not matter because the main point is the global power deviation ΔP.

A difference appears for the global value of load power deviation. Indeed, the principle of the power management of loads is to adjust the load power deviation ΔP^l_{load} depending on the system frequency deviation Δf. It is this simple difference which slows down and finally stops the frequency drop if our time-delay system is asymptotically stable.

In our model, we define values of parameters given in the table 4.4.

Parameter		Value	
The total inertia constant	H	5	$[s]$
The total rating	S_B	4000	$[MW]$
The nominal frequency	f_0	50	$[Hz]$
The frequency-dependency constant	D_L	$\frac{1}{80}$	$[\frac{Hz}{MW}]$
The nominal kinetic energy	W_0	100	$[\frac{MW}{Hz}]$
The frequency deviation for full activation	Δf_{min}	-0.2	$[Hz]$
The number of available quantized loads	N_0	$\{10^6, 10^7, 10^8\}$	$[loads]$
The quantized load	q	50	$[W]$
The time-delay	τ	$\{0.1, 0.5, 1.0\}$	$[s]$

Table 4.4: Values of parameters for the numerical solving of the characteristic equation

We note the majority of parameters are identical to parameters of an uncontrolled power system. This is completely understandable while the power management of loads is added to the uncontrolled power system. We are expanding the parameters by the power management of loads ones: the frequency deviation Δf_{min} for full activation and the threshold for the number of available quantized loads N_0, the quantized load q, and the time-delay τ defining the lag in the system.

As for the power system with primary frequency control in the section 3.6, we need to be aware about the minimal load power deviation ΔP^l_{load} allowed by the power management of loads. From the equation 4.3, this threshold depends on the quantized load q and the number of available quantized loads N_0.

$$\Delta P^l_{load,min} = -p \cdot N_0 \tag{4.28}$$

4.4.1 The variation of the load power deviation

We can observe on the figure 4.5 theoretical responses of the power system with power management of loads by fixing the time-delay τ and the number of available quantized loads N_0, and by varying the load power deviation ΔP^s_{load}. Note we represent only results for upward regulation, results for downward regulation with power management of loads are identical to an uncontrolled power system because the controller is disabled.

According to results about stability in the table 4.2, we choose to fix the time-delay τ equals to 0.2 s and the number of available quantized loads N_0 equals to 10^7 loads. We

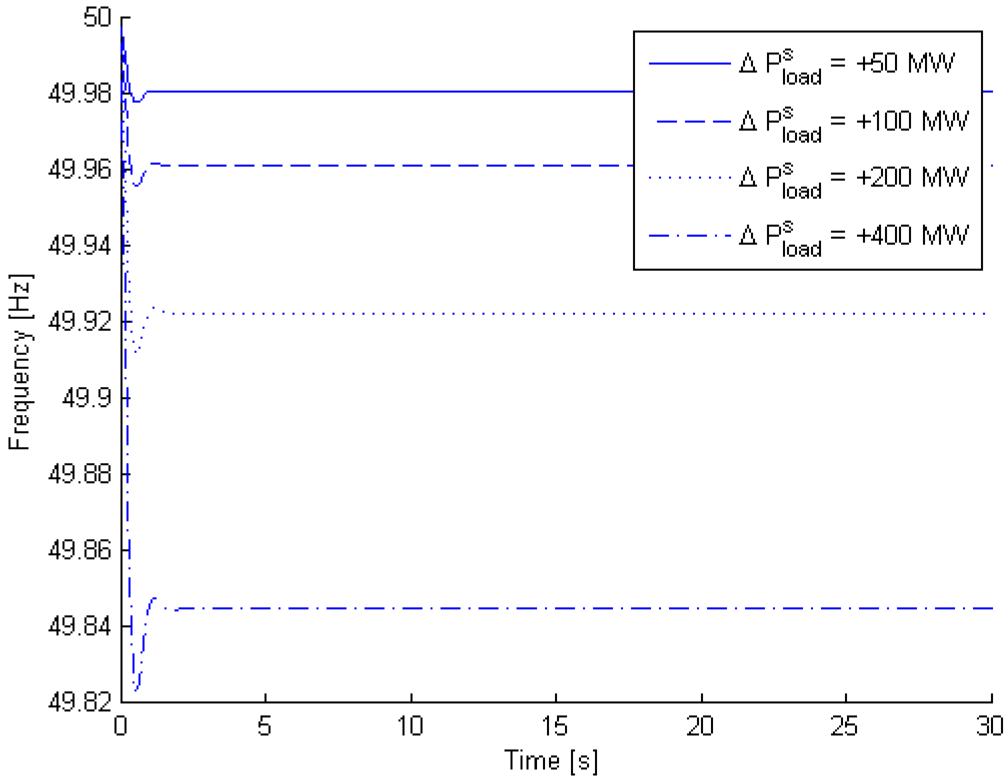

Figure 4.5: Theoretical responses of the power system with power management of loads, comparison on the load power deviation ΔP^s_{load} with $\tau = 0.2$ s and $N_0 = 10^7$ loads.

observe the system frequency f actually converges. By this way, the objective of the power management of loads is reached: the frequency drop is damping and then stopped.

Moreover, the steady-state frequency f is closer to the nominal value f_0 of the system frequency while the load power deviation is smaller. This observation is consistent: the frequency deviation is greater with a more significant disturbance and the time-delay in the system can only accentuate this effect.

From this, it may be legitimate to ask if the steady-state frequency with the power management of loads is identical to the primary frequency control with a same primary reserve? We discuss of it in the subsection 4.4.2.

4.4.2 Comparison with the primary frequency control

We can observe on the figure 4.6 theoretical responses to compare a power system with power management of loads and a power system with primary frequency control. The comparison is done with different primary reserves and with the same ones.

In the dotted and dashed lines, primary reserves are identical. For the primary frequency control, the primary reserve is defined by the speed droop characteristic S and the frequency deviation for full activation. From the equation 3.30, its value is 400 MW. For the power management of loads, the primary reserve is defined by the number of available quantized loads N_0 and the quantized load q. In this case, we choose N_0 to obtain:

$$|\Delta P^l_{load,min}| = |-N_0 \cdot q| = (8 \cdot 10^6) \cdot (50 \cdot 10^{-6}) = 400 \text{ MW} \tag{4.29}$$

In this case, steady-state frequencies are identical: the final frequency deviation from the nominal value is the same with a same primary reserve whatever the method of frequency primary regulation.

In the solid and dashed lines, primary reserves are different. For the primary frequency control, its value is always 400 MW. For the power management of loads, we choose N_0 to have:

$$|\Delta P^l_{load,min}| = |-N_0 \cdot q| = 10^7 \cdot (50 \cdot 10^{-6}) = 500 \text{ MW} \tag{4.30}$$

In this case, we observe steady-state frequencies are different. With a smaller reserve, the final frequency deviation from the nominal value is greater.

4.4.3 The variation of available loads

According to the equation 4.19, more precisely the coefficient $p \cdot \frac{N_0}{\Delta f_{min}}$, a variation of available quantized loads N_0 can be transposed in a variation of the quantized load q or in a

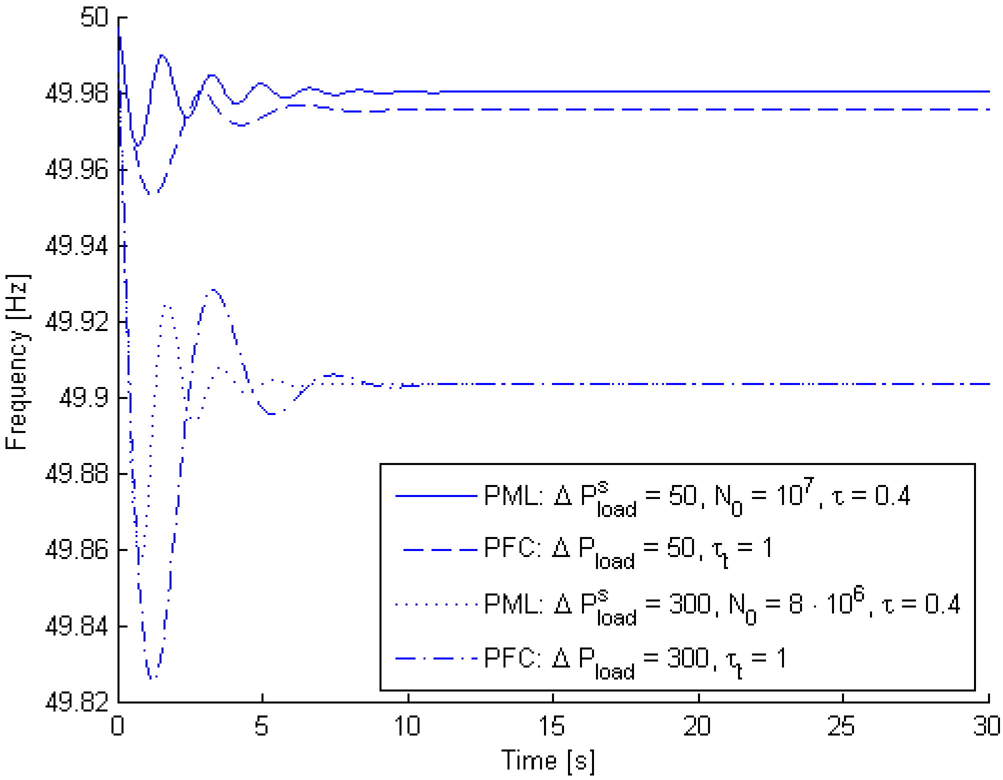

Figure 4.6: Theoretical responses to compare a power system with power management of loads (PML) and a power system with primary frequency control (PFC) with different primary reserves and with the same ones.

variation of the frequency deviation Δf_{min} for full activation. So, discuss about one of them allow us to discuss about the others.

We can observe on the figure 4.7 theoretical responses of the power system with power management of loads by fixing the load power deviation ΔP^s_{load} and the time-delay τ, and by varying the number of available quantized loads N_0.

Foremost, we observe the final frequency deviation from the nominal value is inversely proportional to the number of available quantized loads N_0.

One hand, we have to consider the primary reserve defined by N_0. With a primary reserve much lower than the disturbance through the load power deviation ΔP^s_{load}, the system frequency will tend to behave it self as with an uncontrolled power system. The extreme case is a null number of available quantized loads N_0. If we increase this number, the final frequency deviation from the nominal value decreases.

On the other hand, a number of available quantized loads N_0 too large leads to create oscillations and so instability as for the dotted line. So, we have to find the right balance to stop the frequency drop by keeping the asymptotic stability in the system.

We note this observation is consistent with our computed results for the stability of the time-delay system in the subsection 4.3.2. More precisely, the stability and the instability observed on the figure 4.7 supports results in the table 4.2.

4.4.4 The variation of the time-delay

We can observe on the figure 4.8 theoretical responses of the power system with power management of loads by fixing the load power deviation ΔP^s_{load} and the number of available quantized loads N_0, and by varying the time-delay τ.

Foremost, we observe the final frequency deviation from the nominal value is always the same whatever the time-delay τ. However, the oscillations before to converge increase with the time-delay τ.

With a greater time-delay τ, the power management of loads reacts with a more significant lag. This leads to create instability in the system as supported by the figure 4.8. Intuitively, the lag leads to unnecessary switch off loads. More the lag is important and more will be the number of unnecessary switched off loads.

Moreover, we can see the dotted line is at the limit of convergence. According to results about stability in the table 4.3, we are well at the limit to the asymptotic stability.

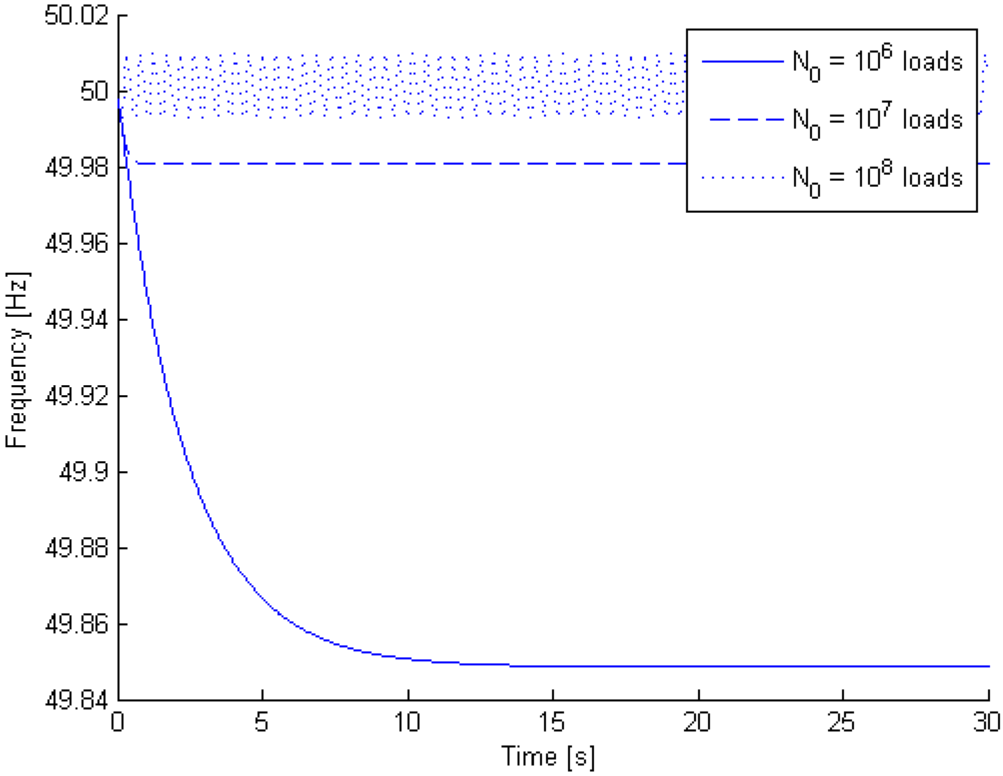

Figure 4.7: Theoretical responses of the power system with power management of loads, comparison on the available loads N_0 with $\tau = 0.1$ s and $\Delta P^{s}_{load} = +50$ MW.

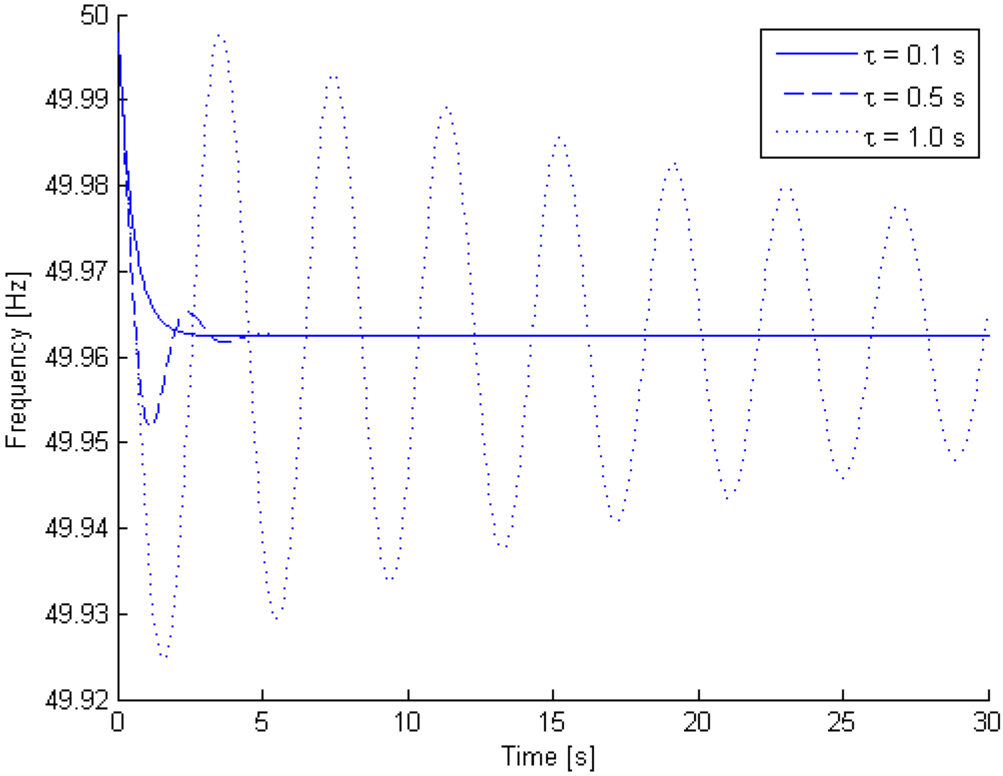

Figure 4.8: Theoretical responses of the power system with power management of loads, comparison on the time-delay τ with $\Delta P^s_{load} = +50$ MW and $N_0 = 5 \cdot 10^6$ loads.

4.4.5 Conclusion

Results show us a power system with power management of loads can be mainly characterized in two ways.

First, the time-delay τ of the power management of loads defines the lag introduced in the power system between the order determined from the frequency deviation Δf and its execution. It is this parameter which defines the speed of convergence and the associated oscillations: there are more oscillations for a greater time-delay τ. However, the system frequency doesn't converge for a too great time-delay τ.

Second, the number of available quantized loads N_0 in the allocation function defines the primary reserve of the power management of loads. With a larger primary reserve, the frequency regulation becomes more efficient. However, the system frequency doesn't converge for a too great number of available quantized loads N_0.

A similar effect can be deduced for both others parameters of the power management of loads. The relation is proportional to the quantized load q and inversely proportional to the frequency deviation Δf_{min} for full activation.

We can note these two ways can be linked with results and conclusion of the primary frequency control. This can be correlated to the allocation function of the power management which has been chosen as a P-controller. Indeed, we only define the proportional gain with extreme boundaries and the time-constant or time-delay for a pure delay.

But there is one notable difference: the primary frequency control ensure the convergence of the system frequency while the power management of loads can lead to instability which prevents the system frequency to converge. This difference appears with the time-delay.

Moreover, we note numerical simulations confirm results about the stability discussed in the subsection 4.3.2. So, it is possible to define parameters to ensure the system frequency is asymptotically stable.

We also observed the steady-state frequency is defined by the primary reserve, and not by the way to stop the frequency drop. The power management of loads is thus not more efficient than the primary frequency control. However, the primary frequency control will generate power through generators in the case of an upward regulation, while the power management of loads will just shift in the time the consumed power.

Our main interest in the power management of loads is a better power management which leads to not generate power to balance the generated power and the consumed power.

In practice, we don't just replace the primary frequency control by the power management of loads. We can imagine to integrate this power management in the current context, but not more. So, how could the power management of loads be integrated in the primary reserve? We attempt to discuss it in the chapter 5.

To expect the integration of a such power management, we have to manage power through all scattered loads. This power management can become possible with an IT platform to manage the aggregate power. We discuss about a possible introduction to software aspects in the chapter 6.

Chapter 5

Transmission System Operator's perspective

In the chapter 4, we introduced and discussed about the power management of loads. We see a way to approach the concept of a power management of loads, and define a model in respect of this concept.

By the emergence of a lag, we were dealing to a time-delay system. So, we develop tools to prove it is possible by an appropriate choice of parameters to ensure a stabilization with an asymptotic stability as for the primary frequency control.

Numerical simulation and results show us the behaviour of the power management of loads may be relatively controlled through its parameters. Except the possibility of instability, this behaviour can be related to the one of the primary frequency control because of the choice to approximate a P-controller.

From there, we can think about the effective integration of the power management of loads in a power system with primary frequency control. Does current standards allow this integration with safety? How can do this? Could primary frequency regulation be more efficient than actually?

In this chapter, we will address theses issues by attempting to answer them by: (1) *an introduction about the limitation of current standards ;* (2) *a description about possible integrations of the power management of loads in a power system with primary frequency control ;* (3) *a presentation of results collected by a numerical simulation of the model.*

5.1 Limitation of current standards

As we have seen previously in the section 3.2, there exists definitions and standards defined for the primary frequency control. Because the concept of power management of loads is not already applied today, there doesn't exist any specific standards for it.

By considering differences between both primary frequency regulation, can we just consider existing standards? Is that appropriated for either the transmission system operator or the power management of loads? Let us look a little closer.

5.1.1 Deficiencies

An important quality for a proper primary frequency control is to respect a maximal time for the physical deployment. Reminder, the primary frequency control must be able to deploy at least 50% of the primary reserve at 15 seconds, and all primary reserve at 30 seconds. This limitation exists because the desired mechanical power deviation ΔP_m^{set} is not instantaneously available as the mechanical power deviation ΔP_m, and so requires a turbine time constant τ_t small enough.

This problem doesn't appear with the power management of loads. Instead, the desired load power deviation $\Delta P_{load}^{l,set}$ is available as ΔP_{load}^{l} after a time-delay τ. In this case, a limitation about a physical deployment should be a minimal boundary time, and not a maximal boundary time which does not make sense. Furthermore, we have to consider the possibility of a depleted portfolio of loads.

Moreover, current standards don't approach the subject of stability. This is perfectly understandable with results about stability for the primary frequency control in the section 3.5: the system frequency is always asymptotically stable. The maximal boundary time of the physical deployment are leading to reduce possible oscillations. However, the power management of loads can introduce instability with a bad choice of parameters.

Address this issue will be necessary. By defining acceptable intervals for parameters and specific protocols, the stability could be ensured or at least reduced the probability of instability. Beyond the scope of this master thesis, we could imagine an interval small enough of frequency deviation Δf which accepts safely oscillations without convergence.

5.1.2 Limitations and improvements

Reminder, UCTE definitions define an interval of frequency deviation where the primary frequency control is enabled. The activation of the primary frequency control is triggered when the frequency deviation exceeds ± 20 mHz, and the full activation of the primary reserve must occur when the frequency deviation exceeds ± 200 mHz.

Because the power management of loads can create power deviation larger in a shorter time than the primary frequency control, we can suggest to consider another interval. For example, the speed activation of the primary reserve, despite a time-delay, allows to quickly reduce the imbalance in the power system. A lower boundary, closer to the null frequency deviation, could be considered.

However, the power management of loads has significant drawbacks compared with the primary frequency control: it is very difficult to forecast the available primary reserve and to measure the load power deviation ΔP^l_{load} really applied. Statistics and safety margin could be prevent wrong forecasts, but it is impossible to precisely forecast a part of the consumed power. That is there the first reason of the imbalance. Moreover, it should be difficult to look at an accurate measure for all scattered loads.

There is to consider difficulties to accurately know the load power deviation ΔP^l_{load} at a given time, and so the real part of the primary reserve which has been activated. That should be problematic for the transmission system operator which has a fixed power for the primary reserve in this area.

5.1.3 Conclusion

We conclude the current standards are clearly defining for the primary frequency control, and not specifically for the primary frequency regulation. Although if it is not explicit, we can note inherent features of the primary frequency control are implicit in current standards. Current standards don't consider a generic primary frequency regulation. So, we can't just respect these standards for the integration and the application of the power management of loads.

However, these standards are not fixed in time and could be evolved to consider the power management of loads as a possible primary frequency regulation. Also, the Belgian transmission system operator are currently discussing[1] to know how integrate and manage load aggregators which could provide a power management of loads.

The subject is thus on the table. Therefore, we can think about the integration in the power management of loads as a primary frequency regulation.

5.2 Integration

According to the previous section, we choose to test two different integrations for the power management of loads.

In the first one, so-called here the *mixed integration*, we keep the frequency deviation interval for activation as for the primary frequency control. In the second one, so-called

[1] This information comes from a student in the MODEPOMA project which made an intern-ship at Elia, the Belgian TSO.

here the *piecewise integration*, we choose to start the power management of loads when the primary frequency control is disabled.

5.2.1 A model

As in previous chapter, the primary frequency control and the power management of loads are inserted as a loop in the uncontrolled power system. Here, we are thus two controller in the power system to stop the system frequency drop. The primary frequency control allows to adjust the mechanical power deviation ΔP_m while the power management of loads allows to adjust a part ΔP^l_{load} of the load power deviation.

The figure 5.1 gives the block diagram of a power system with primary frequency control and with power management of loads. We consider the operation of each controller is exactly the same as describe in sections 3.3 and 4.1.

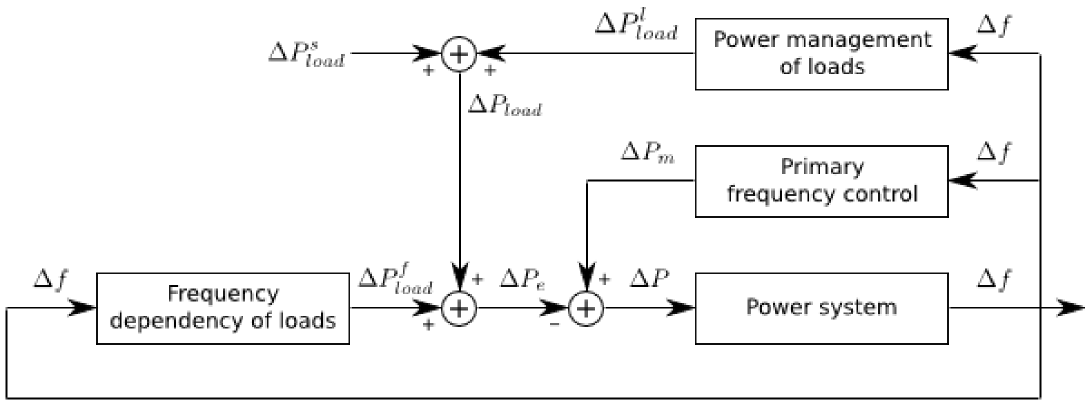

Figure 5.1: Block diagram of a power system with primary frequency control and with power management of loads

We see the system has one input, the part of the load power deviation which can't be managed ΔP^s_{load}, and one output, the frequency deviation Δf.

While a load power deviation ΔP^s_{load} occurs, the power balance between the generated and consumed power in the system is broken leading to a frequency deviation Δf. Our two controllers are there to balance this power imbalance: the primary frequency control can modify the generated power while the power management of loads can modify the consumed power.

However, the generated power can increase and decrease, while the consumed power can only decrease by the controller. Therefore, the suggested model is really applicable for an upward regulation, i.e. to inject generated power or reduce the consumed power. In the case of downward regulation, the power management of loads is disabled and the primary frequency control is the only one to work to the primary frequency regulation.

5.2.2 Mixed integration

In the mixed integration, we enable the primary frequency control and the power management of loads in the same frequency deviation interval for activation. This interval is the same as defined in UCTE standards.

The frequency primary control is enabled from a frequency deviation equals to ± 20 mHz and the full activation from a frequency deviation equals to ± 200 mHz. The power management of loads is enabled from a frequency deviation equals to -20 mHz and the full activation from a frequency deviation equals to -200 mHz.

By considering the allocation function of the power management of loads as a P-controller, power deviations are given in the figure 5.2. We consider the primary reserve for the primary frequency control is equal to 95 MW and the primary reserve for the power management of loads is equal to 5 MW.

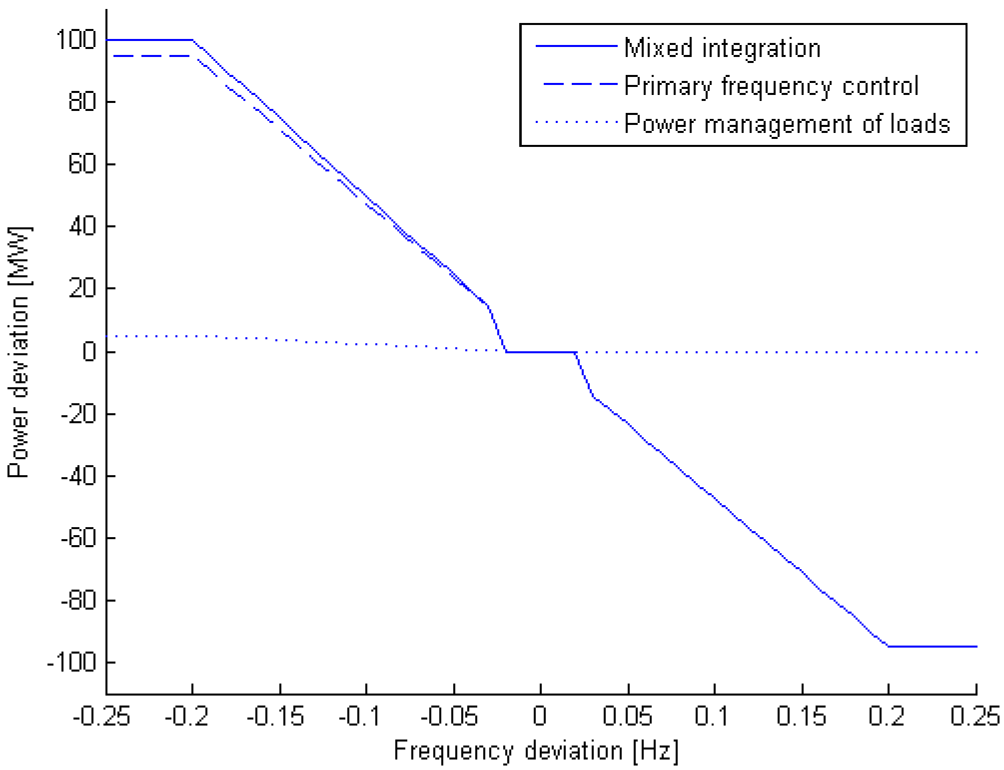

Figure 5.2: Power deviations for the mixed integration

Note the stability of the power management of loads discussed in the section 4.3 assumes that is enabled from 0 Hz. Moreover, there is the primary frequency control to consider in parallel. So, stable values for parameters will be not exactly the same. Because we keep a allocation function as P-controller, the stability can therefore always be ensured.

5.2.3 Piecewise integration

In the piecewise integration, we enable the power management of loads when the primary frequency control is still disabled. By this way, we active a part of the primary reserve with a small frequency deviation while there is an upward regulation. So, we try to quickly balance the generated and consumed power by taking advantage of the rapidity of the power management of loads.

As for the mixed integration, the frequency primary control is enabled from a frequency deviation equals to ± 20 mHz and the full activation from a frequency deviation equals to ± 200 mHz. The power management of loads is enabled from a frequency deviation equals to 0 mHz and the full activation from a frequency deviation equals to -20 mHz.

By considering the allocation function of the power management of loads as a P-controller, power deviations are given in the figure 5.2. We consider the primary reserve for the primary frequency control is equal to 95 MW and the primary reserve for the power management of loads is equal to 5 MW.

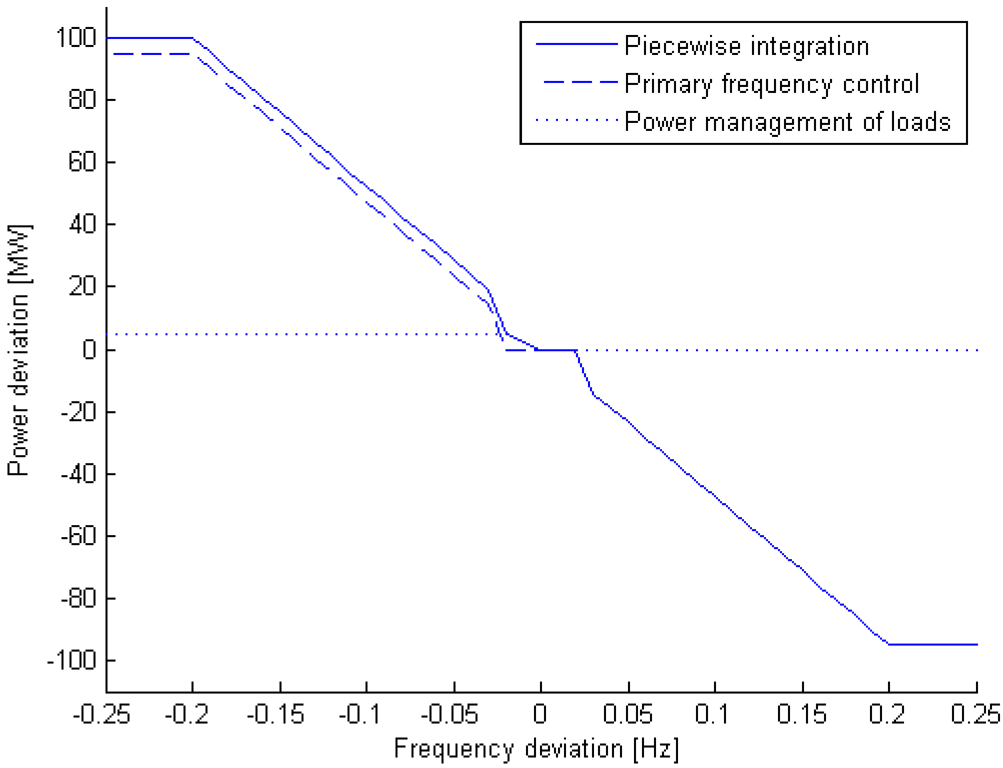

Figure 5.3: Power deviations for the piecewise integration

Note the stability of the power management of loads discussed in the section 4.3 assumes that is enabled from 0 Hz. Moreover, there is the primary frequency control to consider in parallel. So, stable values for parameters will be not exactly the same.

According to the equation 4.19 and the coefficient of the frequency deviation with time-delay $\Delta f(t-\tau)$, if we divide by 10 the frequency deviation Δf_{min}, we have to divide also by 10 the number of available quantized loads N_0 to keep an identical delay differential equation for the power management of loads. However, note the allocation function of the power management of loads is here close to a bang-bang control.

5.3 Numerical simulation and results

5.3.1 The DDE system

From chapters 2, 3 and 4, we can write the considered DDE system which is non-linear:

$$\Delta\dot{f}(t) = \frac{C}{f_0 + \Delta f(t)} \cdot \left(\Delta P_m(t) - \Delta P^s_{load}(t) + a \cdot \Delta f(t-\tau) + b - \frac{1}{D_l} \cdot \Delta f(t)\right) \tag{5.1}$$

$$\Delta\dot{P}_m(t) = \frac{\Delta P_m^{f,set}(t) - \Delta P_m(t)}{\tau_t} \tag{5.2}$$

Where we define Δf_{max} as the frequency deviation to which the activation starts, and:

$$a = p \cdot \frac{N_0}{\Delta f_{min} - \Delta f_{max}} \tag{5.3}$$

$$b = -\Delta f_{max} \cdot a \tag{5.4}$$

$$C = \frac{f_0^2}{(2 \cdot H \cdot S_B \cdot +W_0)} \tag{5.5}$$

With this DDE system, we can build a numerical simulation. To conduct this, we implement the DDE system in Matlab and solve it thanks to the function *dde23*. The source code is available in the appendix A.4.

5.3.2 Parameters

From previous numerical simulations, we keep parameters for the uncontrolled power system. We determine parameters of the primary frequency control to have a primary reserve for upward regulation equals to 95MW, and parameters of the power management of loads to have a primary reserve for upward regulation equals to 5MW.

For the primary frequency control, we have:

$$|\Delta P^{set}_{m,max}| = |\Delta P^{set}_{m,min}| = \frac{|\pm 0.2|}{S} = 95 \text{ MW} \Leftrightarrow S = 2.1 \cdot 10^{-3} \ \frac{\text{Hz}}{\text{MW}} \tag{5.6}$$

For the power management of loads, with a load quantized q equals to 50 W, we have:

$$|\Delta P^{l}_{load,min}| = |-N_0 \cdot (50 \cdot 10^{-6})| = 5 \text{ MW} \Leftrightarrow N_0 = 10^6 \text{ loads} \tag{5.7}$$

In a first approach, we choose to fixed the time-delay τ to a realistic value. Here, we fixed the time-delay τ equals to 1 second.

We resume parameters and their values in the table 5.1.

Parameter		Value	
The total inertia constant	H	5	$[s]$
The total rating	S_B	4000	$[MW]$
The nominal frequency	f_0	50	$[Hz]$
The frequency-dependency constant	D_L	$\frac{1}{80}$	$[\frac{Hz}{MW}]$
The nominal kinetic energy	W_0	100	$[\frac{MW}{Hz}]$
The global speed droop	S	$2.1 \cdot 10^{-3}$	$[\frac{Hz}{MW}]$
The time constant of the turbine	τ_t	5	$[s]$
The frequency deviation for enabling	Δf_{max}	$\{-0.02, 0\}$	$[Hz]$
The frequency deviation for full activation	Δf_{min}	$\{-0.2, -0.02\}$	$[Hz]$
The number of available loads	N_0	10^6	$[loads]$
The quantized load	q	50	$[W]$
The time-delay	τ	1	$[s]$

Table 5.1: Values of parameters for the numerical simulation of the integration of power management of loads

5.3.3 Numerical solving

A first approach

In a first approach, we take value of parameters given in the table 5.1. For comparison, we choose to plot the system frequency regulating by the primary frequency control for a same disturbance and with a primary reserve of 100 MW. According to the equation 5.6, the speed droop characteristic S is so equal to $2 \cdot 10^{-3}$ $\frac{\text{Hz}}{\text{MW}}$.

The figure 5.4 gives a comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for a disturbance $\Delta P^s_{load} = +50$ MW.

Foremost, we see the mixed integration is less efficient than the primary frequency control. The difference is almost equal to zero. We can suppose the difference appears because of the lag introduced by the power management of loads. Indeed, we can see the dynamic frequency is more important for the mixed integration: there is a lag to react for a part of the primary reserve.

Then, we see the piecewise integration leads to an oscillation of the system frequency. However, we can note the value of maximum dynamic frequency is less than the half of the maximum dynamic frequency for the primary frequency control or the mixed integration.

As discussed in the subsection 5.1.1, if oscillations are accepted and controlled in a small frequency deviation interval, that could be interesting. Firstly, the system frequency drops less significantly with a same primary reserve. Secondly, the system frequency is coming back close to its nominal value because of oscillations. It is not the purpose of the primary frequency regulation, but that could help the secondary frequency regulation.

A second approach

In a second approach, we try to obtain a stabilization of the system frequency for the piecewise integration in order to compare it to others. As concluded in the section 4.4, we can stabilize results of the power management of loads by decrease the number of available quantized loads N_0 or the time-delay τ. Here, we keep the time-delay τ and we reduce the number of available quantized loads N_0. We choose to divide by 10 its value, and so the primary reserve from the power management of loads decreases to 0.5 MW.

The figure 5.5 gives a comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for a disturbance $\Delta P^s_{load} = +50$ MW and a number of available loads $N_0 = 10^5$ loads.

We see the piecewise integration is more efficient than the others despite its global primary reserve is less important. We can suppose the difference comes from a part of the primary reserve activates more quickly. So, the imbalance is reduced more quickly and the system frequency drops less significantly.

A third approach

In a third approach, we can ask us if these results will be the same with different disturbance. We increase the disturbance with parameters as for the first approach, i.e. integrations have a primary reserve of 100 MW.

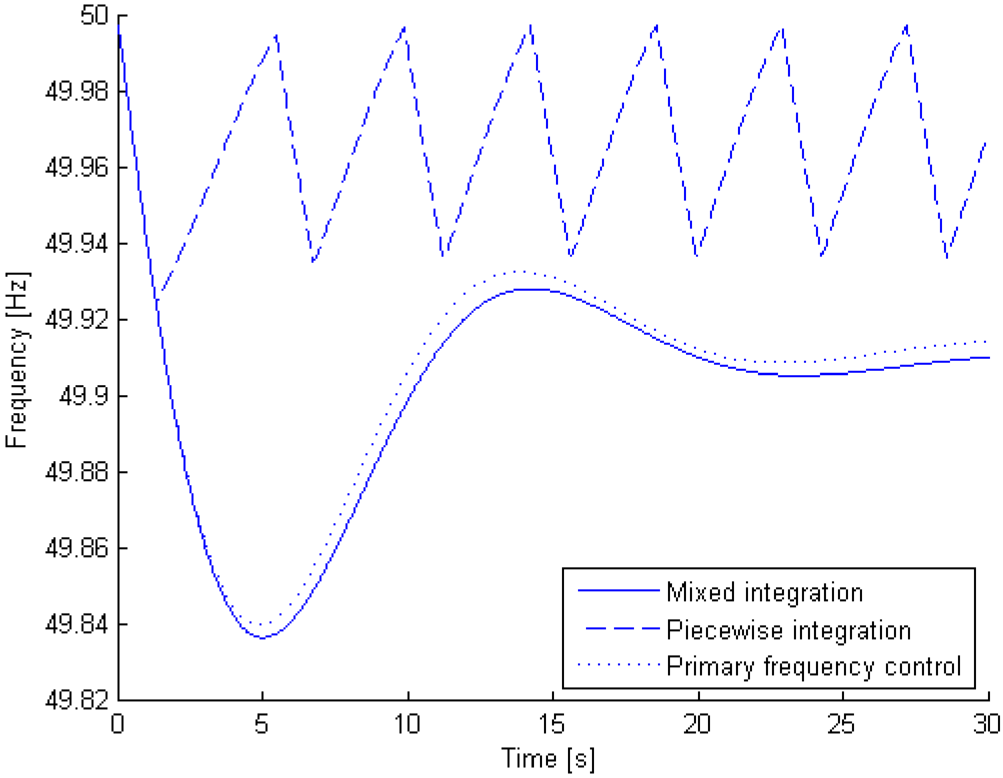

Figure 5.4: Comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for $\Delta P^s_{load} = +50$ MW

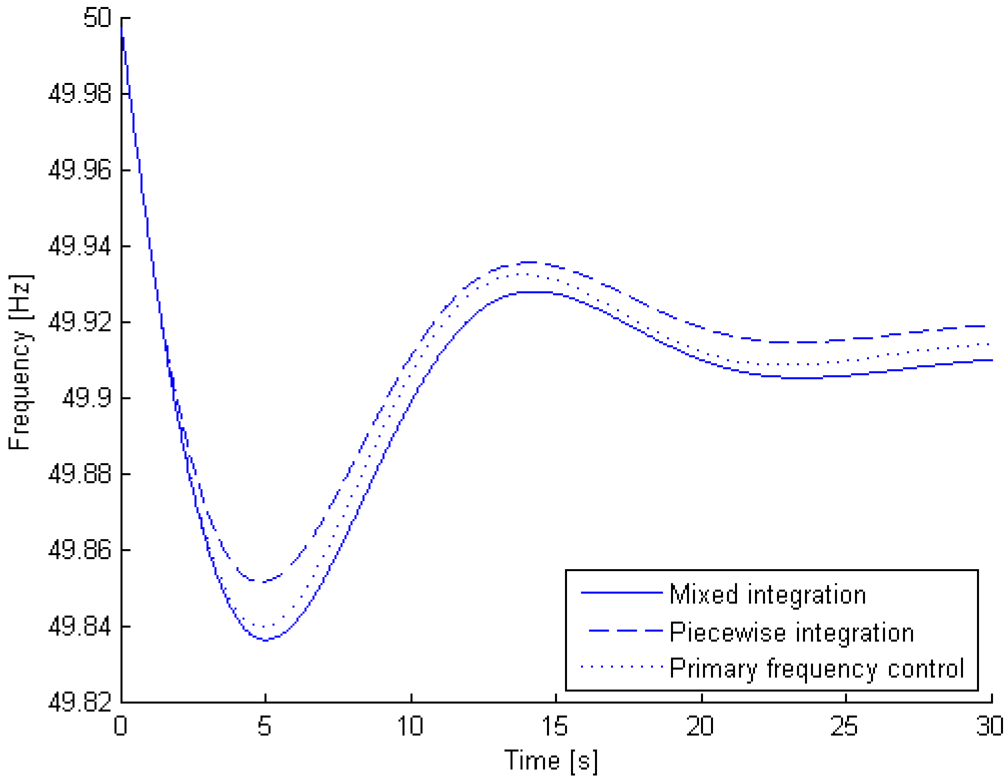

Figure 5.5: Comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for $\Delta P^s_{load} = +50$ MW and $N_0 = 10^5$ loads

The figure 5.6 gives a comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for a disturbance $\Delta P^s_{load} = +80$ MW.

Foremost, we can note the weird shape of the system frequency with the mixed integration. This can be linked to the threshold for full activation which is passed: oscillations appear with a full activation of the power management of loads, but disappear while the behaviour comes back to a P-controller. The system frequency can so converge. However, that doesn't seem more efficient than the primary frequency control.

Then, we can see the piecewise integration doesn't create oscillations any more. In this case, the difference on the results between the piecewise integration and the others is always more significant: almost one third. That could be linked to the primary reserve which is the same here.

A fourth approach

As for the third approach, we get results for a different disturbance. In the fourth approach, we decrease the disturbance with parameters as for the first approach, i.e. integrations have a global primary reserve of 95.5 MW.

The figure 5.7 gives a comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for a disturbance $\Delta P^s_{load} = +20$ MW and a number of available loads $N_0 = 10^5$ loads.

Here, no surprise: the piecewise integration is more efficient than the others, and the mixed integration stays less efficient than the primary frequency control.

Conclusion

Theoretical results allow us to conclude differently for the two kinds of integrations introduced in the section 5.2.

About the mixed integration, it is always less efficient than the primary frequency control. The power management of loads introduces a lag which leads to reduce the imbalance later. However, its application could be found an interest when the disturbance leads to a frequency deviation lower than the lower boundary for full activation. In this case, the maximum dynamic frequency is less important and the system frequency converges more quickly.

About the piecewise integration, it is always more efficient than the primary frequency control. However, we have to consider two aspects.

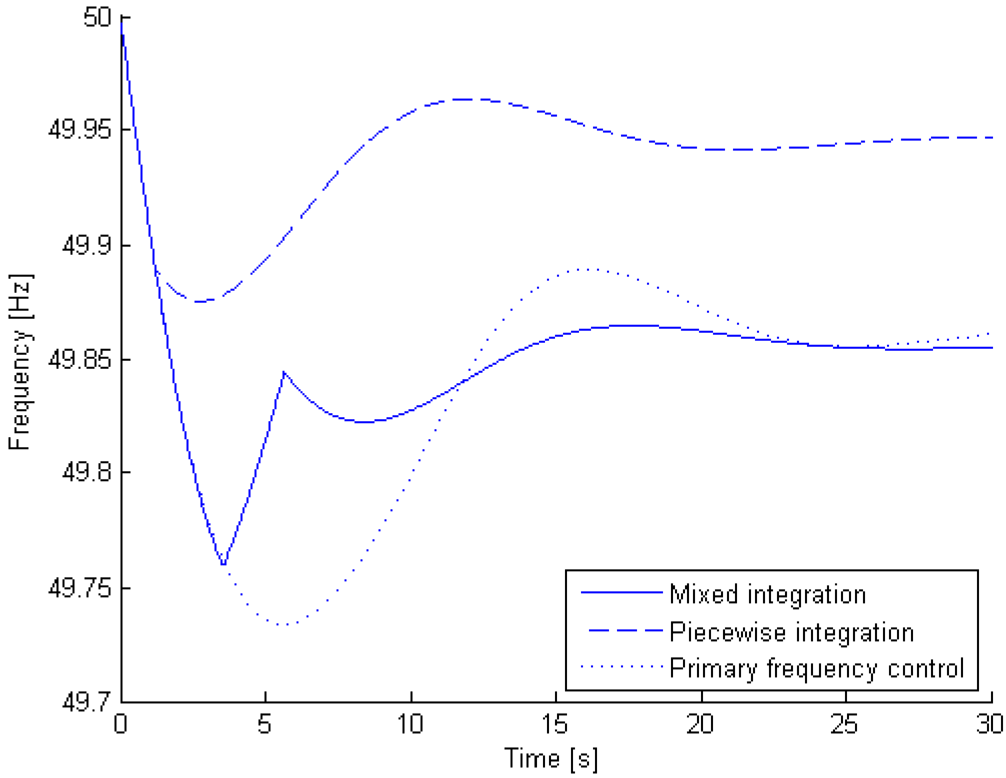

Figure 5.6: Comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for $\Delta P^{s}_{load} = +80$ MW

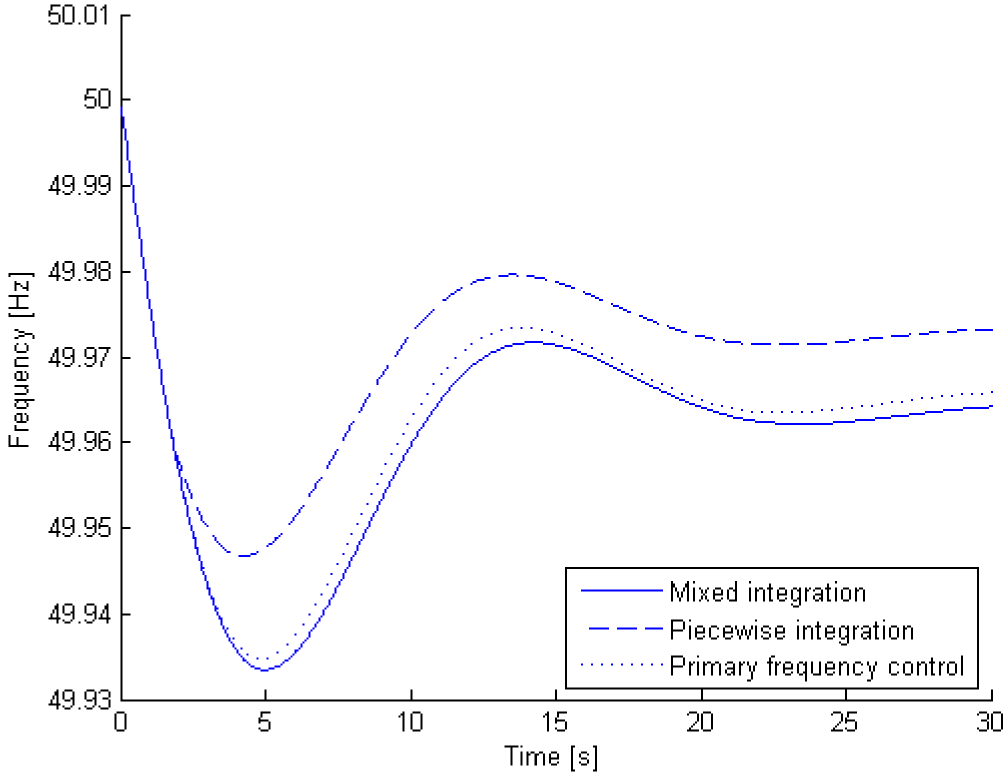

Figure 5.7: Comparison about theoretical responses for a power system with primary frequency control, with mixed integration and with piecewise integration, for $\Delta P^{s}_{load} = +20$ MW and $N_0 = 10^5$ loads

The first one is when the power management of loads leads to oscillations of the system frequency. In this case, the maximum dynamic frequency is less important than others. These oscillations could allow to come back more easier the system frequency to its nominal value. Nevertheless, introduce oscillations for the system frequency must be controlled. Guardrails should be introduced to ensure oscillations just disappear when we want.

The second one is when the power management of loads leads to an asymptotic stabilization of the system frequency. In this case, the piecewise integration is always more efficient than the other possibilities. And the best being, this efficiency appears with a global primary reserve less important. Moreover, the part of primary reserve for the power management of loads can be insignificant compared to that of the primary frequency control, the efficiency is always there.

That solves the big problem to have to aggregate a considerable amount of loads before to integrate the market. So, a better management of the power is better than just more power.

Finally, we conclude the integration of the power management of loads in the power system with primary frequency control could be really efficient. The frequency deviation is lower and that leads to reduce the generation of the primary reserve.

Chapter 6

Introduction to software aspects

In chapters 4 and 5, we discussed about the power management of loads as primary frequency regulation and a possible integration in the current context of a power system as the grid. It remains an important issue to introduce: how can we manage a primary reserve composed by loads scattered across the power system? An answer can be introduced by considering software aspects.

The purpose of the power management of loads is to control quickly and efficiently an aggregated power through an amount of loads. A software component is thus necessary. In this chapter, we give an possible introduction to software aspects by considering requirements. These requirements have to respect all previous concepts we discussed in this master thesis.

In this chapter, we introduce to software aspects by: (1) *an identification of assumptions and the purpose of software aspects ;* (2) *an identification of constraints related to an IT platform ;* (3) *a description about actors and their relationships ;* (4) *an identification of main use cases.*

6.1 Assumptions and purpose

In the context of this master thesis, we don't have results at a business or marketing level of the power management project as a primary frequency regulation. So, we have to make some assumptions and clearly define the purpose of our software system.

Assumptions

We assume an aggregator of loads provides a primary frequency regulation. The aggregator of loads manages loads contained in batteries by contracting directly with battery owners. A battery owner can be an individual, a representative of a group of individuals or an industrial, and can give control of one or more batteries with some restrictions.

We focus software aspects on an IT platform which allows to manage the aggregated power through batteries. In our introduction, we consider the software, and the corresponding hardware, of the battery side as a black box working with any problem.

We assume the IT platform allows a primary frequency regulation thanks to the direct measurement of the frequency deviation. This service is provided to only one Transmission System Operator. So, we have no area restriction about batteries. Moreover, we consider the primary reserve market have any entry barrier about the minimum power to provide as primary frequency regulation.

Purpose

The purpose of our IT platform is to provide two services.

The first one is a primary frequency regulation, continually and automatically, by a power management of loads. Therefore, the IT platform manages all loads and sends necessary data to the Transmission System Operator. Parameters about the power management of loads can be defined and changed.

The second one is to make available data to the battery owners about their batteries. There are dynamic data about the current state of the aggregated power and static data about statistics.

6.2 Constraints

We have to consider some constraints to meet properly the purpose of our software system. We grouped this in four points: communication security, time-delay, data integrity and measurement accuracy.

6.2.1 Communication security

If a communication transmitted or received by the IT platform is altered by a stranger of the software system, the security of the system may be dangerously compromised. A risk is the development of a lot of disturbances in the power system, but another big one is this stranger could manage aggregate power to create a black out by intention. So, it is very important to ensure the safety of all communications.

From [KR10], following properties allow to ensure the communication is secure.

- *Confidentiality.* Only the sender and intended receiver should be able to understand the contents of the transmitted message. Because the message may be intercepted, this necessarily requires that the message be somehow encrypted. So, an intercepted message cannot be understood by an interceptor.

- *End-point authentication.* Both the sender and receiver should be able to confirm the identity of the other party involved in the communication. That necessarily requires there is an authentication of each party.

- *Message integrity.* Even if the sender and receiver are able to authenticate each other, they want to ensure that the content of their communication is not altered accidentally or intentionally.

6.2.2 Time-delay

The time-delay is a parameter of the power management of loads. Its value is significant to ensure an asymptotic stability of the system frequency. However its value can't be simply fixed. The propagation delay have to be considered to ensure a proper and desired behaviour.

The establishment of a continuous discussion allows to compute statistics about the time-delay and to get feedback about the execution of orders. A time-out as network parameter will trigger an event to replace the corresponding load while a predetermined time elapses.

Moreover, we have to keep in mind that we study the frequency dynamics for a power system with power management of loads where we assume the time-delay is constant and fixed. In practice, we could consider the real time-delay and a latency time at the level of the mobile device to keep a global constant time-delay.

6.2.3 Data integrity

We can decompose all data in two parts according to volatility: dynamic and static data. Dynamic data mainly concern the current operation of the software system providing a primary frequency regulation. Static data mainly concern statistics for members and the transmission system operator, and the behaviour of the power management of loads.

A loss or a corruption of data will be very problematic and would hinder to a proper work. So, there is necessity to ensure a physical integrity and a coherence integrity. The first one can be achieved by a duplicated storage and back up of data. The second one can be achieved by defining specific protocols.

6.2.4 Measurement accuracy

Following the data integrity, another considered point is the data accuracy. The whole power management of loads depends of the frequency deviation in the power system. To have a proper output of the power management of loads, the input must be correct. An incorrect input will undoubtedly leads to an incorrect output. An improper response in the power system can be led to the opposite effect to that desired.

Especially, the measurement accuracy of the frequency deviation must be small enough to be neglected with no risk. For example reminder the section 3.2, UCTE standards define the accuracy of frequency measurements must be at least 10 mHz. The presence of multiple measurement tools can be reduced the risk of error.

6.3 Actors

We consider the IT platform as the software system to determine the different actors.

The *aggregator of loads* is the legal entity which provides the power management of loads through its IT platform. That allows it to provide a primary frequency regulation to the *Transmission System Operator*. The aggregator employs *system administrators* which manage the platform and ensure its proper operation.

The scattered loads through the power system compose the *aggregate power*. The IT platform can regulate this power. These loads are contained in *batteries*. The aggregator of loads directly contracts with battery owners to manage it. Regardless of what they represent, a battery owner is so-called a *member*.

To know what to do, the IT platform receive informations about the frequency deviation in the *power system* thanks to *measurement tools*.

Finally, we assemble all information about actors and their relationships in a static structure given in the figure 6.1.

6.4 Use cases

To define requirements, we finally determine a set of typical interactions between the software system and its environment. We capture some features by defining use cases with high-level purposes. Use cases are given in tables 6.1 to 6.10.

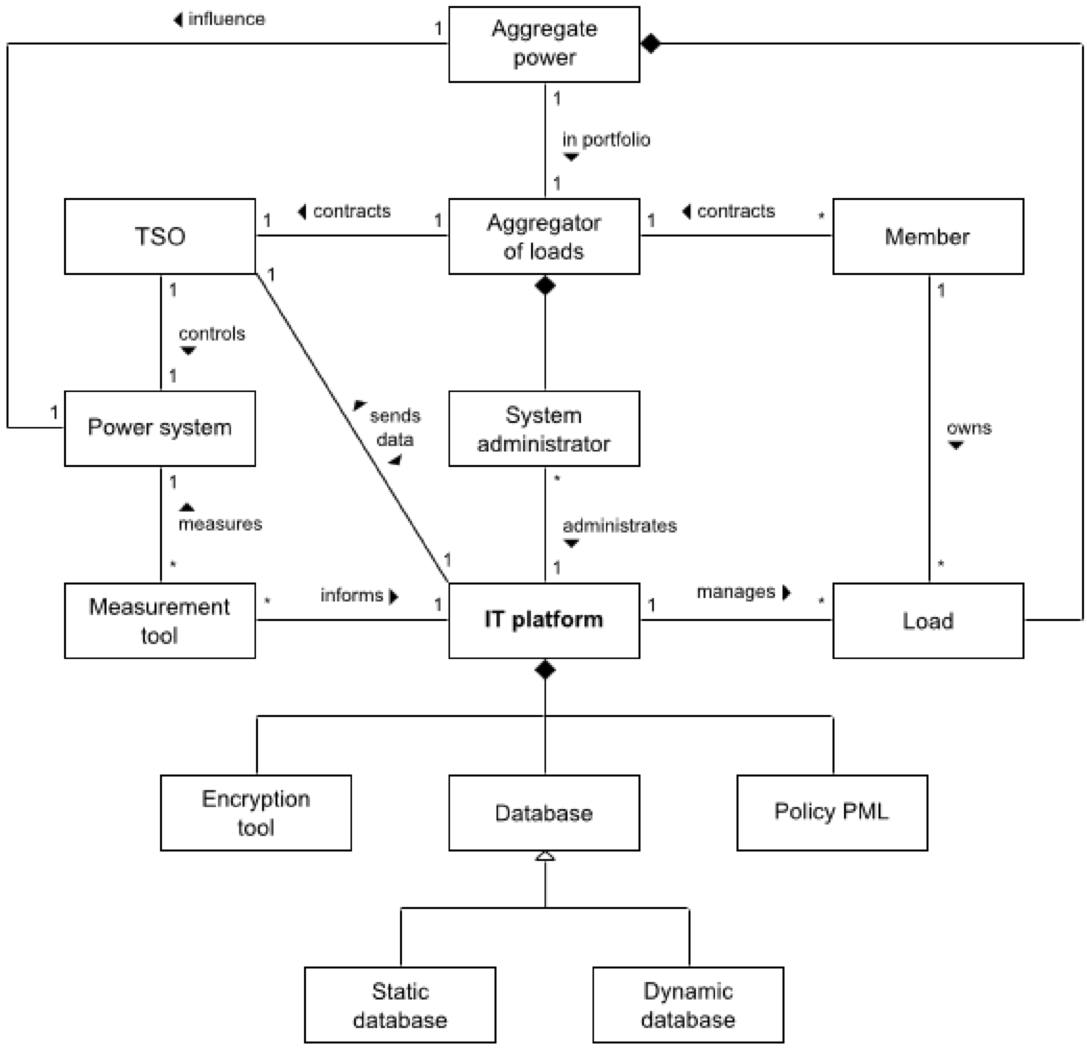

Figure 6.1: Static structure about actors and their relationships

View data as current state	
Actor(s)	Member, System administrator
Purpose	View data as current state, i.e. the state of batteries in the current aggregated power.
Overview	A system administrator asks to the IT Platform to display data as the current state. The IT platform gets data from the dynamic database and displays it. Displaying is updated in the same time as the dynamic database. For a member, that only focus on its own batteries by an interface with an identification.

Table 6.1: Use case - View data as current state

View data as statistics	
Actor(s)	Member, System administrator
Purpose	View data as statistics, i.e. the past behaviour of the power management of loads and past state of batteries.
Overview	A system administrator requests to the IT platform to display data as statistics. The IT platform gets data from the static database and displays it. Displaying is not updated in the same time as the static database. For a member, that only focus on its own batteries.

Table 6.2: Use case - View data as statistics

Modification of a system parameter	
Actor(s)	System administrator
Purpose	Modification of a system parameter, i.e. a parameter defining the power management of loads.
Overview	A system administrator requests to the IT platform to display current system parameters, chooses the one to modify and defines its new value. The system administrator accepts and saves. The IT platform checks if the value is acceptable and saves the new value, else it occurs an error and display informations to the system administrator without saving it.

Table 6.3: Use case - Modification of a system parameter

Modification of a personal data	
Actor(s)	Member, System administrator
Purpose	Modification of personal data, i.e. an information about a member and its batteries.
Overview	The member identifies itself to the interface to consult the IT platform data, requests to the IT platform to display its personal data, chooses the one to modify and defines its new value. The member accepts and saves. The IT platform saves the new value and checks if its modification needs a notification to a system administrator because it could lead to modify the behaviour of the power management of loads.

Table 6.4: Use case - Modification of a personal data

Measurement of a frequency deviation	
Actor(s)	Aggregate power, Batteries, Measurement tools, Power system
Purpose	A measurement of a frequency deviation leads to a primary frequency regulation according to the power management of loads.
Overview	Measurement tools indicate a frequency deviation in the power system to the IT platform. According to the policy defined for the power management of loads, the IT platform determines the load power deviation to apply thanks to the aggregated power. The IT platform can manage batteries composing the aggregated power through a communication with each of them. The IT platform must control: on the one hand, the load power deviation at a given instant, and on the other hand, the proper use of batteries according to associated personal data and their current states.

Table 6.5: Use case - Measurement of a frequency deviation

Adding of a member	
Actor(s)	Aggregator of loads, Member, System administrator
Purpose	Adding a new member which contracts with the aggregator of loads.
Overview	A member contracts with the aggregator of loads and have to be added to database of the IT platform. One possibility is a system administrator directly encodes data about the member through the IT platform. Another one is the member contracts by an interface linked to the IT platform and encodes itself its personal data, which could be accepted by a system administrator before its activation.

Table 6.6: Use case - Adding of a member

Communication with a battery	
Actor(s)	Battery
Purpose	Communication between the IT platform and a battery.
Overview	The IT platform wants to communicate with a battery, or inversely. To ensure secure communication, the message is encrypted by the sender and will be decrypted by the receiver by ensuring its authenticity and its integrity. The IT platform can send pre-defined requests to get information or to change the state of the battery. The battery can send information about itself and confirm the good execution of an order.

Table 6.7: Use case - Communication with a battery

Communication with the TSO	
Actor(s)	Aggregator of loads, TSO
Purpose	Communication between the aggregator of loads, through the IT platform, and the TSO.
Overview	By contract between the aggregator of loads and the transmission system operator, the aggregator of loads must regularly send data about the primary frequency regulation to the TSO. To ensure secure communication, the message is encrypted by the sender and will be decrypted by the receiver by checking its authenticity and its integrity. The IT platform can send statistics required by the transmission system operator.

Table 6.8: Use case - Communication with the TSO

Connection of a battery	
Actor(s)	Aggregate power, Battery, Member
Purpose	Connection of a battery for a registered member.
Overview	A member can connect a battery to the aggregate power. The interface of the battery communicates with the IT platform to indicate its presence and its state. The IT platform updates the dynamic data about the connected battery and can use it for the primary frequency regulation.

Table 6.9: Use case - Connection of a battery

Disconnection of a battery	
Actor(s)	Aggregate power, Battery, Member
Purpose	Disconnection of a battery for a registered member.
Overview	A member can disconnect a battery to the aggregate power, or the battery can be unintentionally disconnected. The IT platform will be notified of the disconnection with a time-out in the communication with the disconnected battery. The IT platform updates the dynamic data about the disconnected battery to no longer count on it for the primary frequency regulation.

Table 6.10: Use case - Disconnection of a battery

Chapter 7

Conclusion

At the time to conclude, we think this master thesis answers to the purpose defined in the introduction.

We give an overview on what already exists about the uncontrolled power system and about a power system with primary frequency control. We describe precisely mechanisms necessary to understand how works the frequency regulation thanks to ordinary differential equations. This overview was intended to allow the introduction of the power management of loads. So, we add an approach on the stability which we will be useful for further.

Thanks to numerical simulations, we discuss results to identify advantages and limitations. A power system as the grid needs frequency control to stop the frequency drop, and the primary frequency control properly works to reach the objective. However, limitations appear in the inherent nature of the primary frequency control and opportunities arise in a context where smart grid becomes a workhouse.

We introduce the concept of the MODEPOMA project by modelling the power management of loads. We define mechanisms to equate this frequency control as a delay differential equation by identifying the frequency control as a P-controller. By the presence of a time-delay, the problem of the stability becomes more complex. So, we develop tools to compute parameters to ensure an asymptotic stability thanks to the characteristic equation which is a transcendental equation. By this way, we demonstrate the system frequency can converge with a right choice about parameters.

Thanks to numerical simulations, we discuss results to prove the power management of loads could be work properly as the primary frequency control. The main difference is the possibility for the power management of loads to create oscillations in the system with a bad choice of parameters. Except this consideration, the objective to stop the frequency drop is reached, and the power management of loads could work.

The question was then whether there is an interest to integrate the power management of loads in parallel to the primary frequency control. Foremost, we discuss about current standards to show its limitations for the power management of loads. Current standards implicitly consider inherent features specific to the primary frequency control. Fortunately, these standards are not fixed and could evolve by the emergence of load aggregators.

We imagine thus two possibilities of integration: a first one so-called the mixed integration which respects the current standards, and a second one so-called the piecewise integration which takes advantage of inherent qualities of the power management of loads.

Thanks to numerical simulations, we discuss results to determine if an integration could be interesting. We show the mixed integration is globally less efficient than just the primary frequency control. Contrariwise, the piecewise integration is clearly the most efficient. We can obtain a smaller frequency deviation by a primary reserve of only 0.5% of the initial primary reserve for the primary frequency control.

There are thus several interests to this integration. The first one is the possibility to reduce the primary reserve for a same frequency control. The security could be therefore increase. The second one is to take advantage of a smart grid approach: we just manage in a better way the power stored and connected on the grid, rather than a systematic power generation.

Finally, we define a possible introduction to software aspects. With all information about the frequency dynamics, we introduce requirements to a software support for the power management of loads. This software support could take the shape of an IT platform.

From the study of the frequency dynamics and this introduction to software aspects, we give theoretical basis as a concept to understand how could work the power management of loads. So, we open a door and we just can go the next level. A first step could be the implementation of an IT platform as a proof of concept.

Appendix A

Source code

The following source code can be downloaded at `http://www.student.montefiore.ulg.ac.be/~s062826/TFE/`.

A.1 Uncontrolled power system

Listing A.1: solveUPS.m

```
function [t, f] = solveUPS(dp_load)
%SOLVEUPS   Solve the Uncontrolled Power System (UPS) as an ODE system.
%   [T,F] = SOLVEUPS(DP_LOAD)
%   I:  DP_LOAD       the constant load power deviation     [MW]
%   O:  T             the time t                            [s]
%       F             the system frequency at time t        [Hz]

% Parameters of the UPS
global D_l f_0 H S_B W_0
D_l = 1/80;        % the frequency dependency constant [Hz/MW]
f_0 = 50;          % the nominal frequency             [Hz]
H = 5;             % the total inertia constant        [s]
S_B = 4000;        % the total rating                  [MW]
W_0 = 100;         % the nominal kinetic energy        [MW/Hz]

% Inputs of the UPS
global Delta_P_load Delta_P_m
Delta_P_load = dp_load;      % the load power deviation              [MW]
                             %       (frequency-independent)
Delta_P_m = 0;               % the mechanical power deviation        [MW]

% Solve the ODE system thanks to the ODE45 function
t0 = 0;            % the lower bound of integration    [s]
t_final = 60;      % the upper bound of integration    [s]
y0 = [0];          % the initial condition             [Hz]
options = odeset(...
    'RelTol', 1e-3); % the relative error tolerance
[y_out] = ode45(@sysUPS, [t0 t_final], y0, options);

% Determine the output of the system
```

```
t = linspace(t0, t_final, 1000);    % the time
y = deval(y_out, t);                % the frequency deviation
f = f_0 + y;                        % the system frequency

end
```

Listing A.2: sysUPS.m

```
function [f] = sysUPS(T, Y)
%SYSUPS Represent the ODE system of the Uncontrolled Power System (UPS).
%   [F] = SYSUPS(T,Y)
%   I:  T       the time t
%       Y(1)    the frequency deviation at time t
%   O:  f       the function f as y' = f(T, Y)
%       f(1)    the derivative of the frequency deviation at time t

% Parameters of the UPS
global D_l W_0 f_0 H S_B

% Inputs of the UPS
global Delta_P_load Delta_P_m

% Ancillary parameter
Coef = f_0 * f_0 / (2 * (H * S_B + W_0));

% Compute the function f
f(1) = (Delta_P_m - Delta_P_load - Y(1) / D_l) * Coef / (f_0 + Y(1));
f = f';

end
```

A.2 Power system with primary frequency control

Listing A.3: solvePFC.m

```
function [t, f, dp_m] = solvePFC(dp_load, time_c)
%SOLVEPFC   Solve the power system with Primary Frequency Control (PFC) as
%an ODE system.
%   [T,F,DP_M] = SOLVEPFC(DP_LOAD,TIME_C)
%   I:  DP_LOAD     the constant load power deviation       [MW]
%       TIME_C      the time constant of the turbine        [s]
%   O:  T           the time t                              [s]
%       F           the system frequency                    [Hz]
%       DP_M        the mechanical power deviation          [MW]

% Parameters of the UPS
global D_l f_0 H S_B W_0
D_l = 1/80;       % the frequency dependency constant [Hz/MW]
f_0 = 50;         % the nominal frequency             [Hz]
H = 5;            % the total inertia constant        [s]
S_B = 4000;       % the total rating                  [MW]
```

```
W_0 = 100;         % the nominal kinetic energy          [MW/Hz]

% Parameters of the PFC
global S tau_t
S = 1/2000;        % the speed droop                      [Hz/MW]
tau_t = time_c; % the time constant of the turbine    [s]

% Input of the system
global Delta_P_load
Delta_P_load = dp_load; % the load power deviation            [MW]
                        %       (frequency-independent)

% Solve the ODE system thanks to the ODE45 function
t0 = 0;            % the lower bound of integration     [s]
t_final = 30;      % the upper bound of integration     [s]
y0 = [0 0];        % the initial conditions              [Hz MW]
options = odeset(...
    'RelTol', 1e-3); % the relative error tolerance
[y_out] = ode45(@sysPFC, [t0 t_final], y0, options);

% Determine the output of the system
t = linspace(t0, t_final, 1000);    % the time
y = deval(y_out, t);                % (1,:) the frequency deviation
                                    % (2,:) the mechanical power deviation
f = f_0 + y(1,:);    % the system frequency
dp_m = y(2,:);       % the mechanical power deviation

end
```

Listing A.4: sysPFC.m

```
function [f] = sysPFC(T, Y)
%SYSPFC Represent the ODE system of the power system with Primary Frequency
%Control (PFC).
%   [F] = SYSPFC(T,Y)
%   I:  T        the time t
%       Y(1)     the frequency deviation at time t
%       Y(2)     the mechanical power deviation at time t
%   O:  f        the function f as y' = f(T, Y)
%       f(1)     the derivative of the frequency deviation at time t
%       f(2)     the derivative of the mechanical power deviation at time t

% Parameters of the UPS
global D_l f_0 H S_B W_0

% Parameter of the PFC
global tau_t

% Input of the system
global Delta_P_load

% Local variable
Delta_P_set_m = controlLoop(Y(1));
```

```
% Ancillary parameter
Coef = f_0 * f_0 / (2 * (H * S_B + W_0));

% Compute the function f
f(1) = (Y(2) - Delta_P_load - Y(1) / D_l) * Coef / (f_0 + Y(1));
f(2) = (Delta_P_set_m - Y(2)) / tau_t;
f = f';

end
```

Listing A.5: controlLoop.m

```
function [p] = controlLoop(Y)
%CONTROLLOOP    Determine the mechanical power deviation to apply from
    a
%frequency deviation.
%   [P] = CONTROLLOOP(Y)
%   I:  Y   the frequency deviation                         [Hz]
%   O:  p   the mechanical power deviation to apply         [MW]

% Parameter of the PCF
global S

% Compute the mechanical power deviation
if abs(Y) < 0.02            % the control loop is disabled
    p = 0;
elseif abs(Y) < 0.2         % the control loop is enabled
    p = - Y(1) / S;
else                        % full activation of the primary reserve
    p = - 0.2 * sign(Y(1)) / S;
end

end
```

A.3 Power system with power management of loads

A.3.1 Stability

Listing A.6: stabilityPML.m

```
function [stableValues] = stabilityPML(variable, fixedValue, testValues
    )
% STABILITYPML  Solves the characteristic equation for the power system
% with Power Management of Loads (PML), by fixing the value of the
    chosen
% variable and test given values for the other variable. It returns
    values
% whose eigenvalues have a strictly negative real part, and for which
    the
% system is asymptotically stable. Variables which can be tested are
    the
% constant number of available loads N_0 and the time-delay tau.
```

```
%    [STABLEVALUES] = STABILITYPML(VARIABLE, FIXEDVALUE, TESTVALUES)
%    I:  variable         the variable to fix
%                         - 1: the number of available loads N_0  [loads]
%                         - 2: the time-delay tau                 [s]
%        fixedValue       the value of the variable to fix
%        testValues       values to test for the other variable
%        O:  stableValues     values tested for which the system is
%                         asymptotically stable
%    Examples:
%        tau = stabilityPML(1, 1e6, 1e-1:1e-1:5);
%        N_0 = stabilityPML(2, 1, 1e6:1e6:1e9);

% Parameters of the UPS
global D_l f_0 H S_B W_0
D_l = 1/80;       % the frequency dependency constant [Hz/MW]
f_0 = 50;         % the nominal frequency             [Hz]
H = 5;            % the total inertia constant        [s]
S_B = 4000;       % the total rating                  [MW]
W_0 = 100;        % the nominal kinetic energy        [MW/Hz]

% Initiliaze results
stableValues = [];

% Parameters of the PFC
global Delta_f_min p
Delta_f_min = -0.2; % the frequency deviation threshold [Hz]
p = 50e-6;          % the quantized load                [MW]

% Variables of the PFC
global N_0 tau
if variable == 1
    N_0 = fixedValue;     % the number of available loads    [loads]
elseif variable == 2
    tau = fixedValue;     % the time-delay                   [s]
else
    return;
end

% Parameters for the solver
options = optimset(...
    'Display','off',... % the level of display
    'TolFun',1e-3,...   % the termination tolerance on the function value
    'MaxIter',1e6);     % the maximum number of iterations allowed
x_0 = i;                % the initial condition whose the imaginary part is
                        % not null to ensure to converge for complex roots

% Iteration to test values for the unfixed variable
for k = testValues
    % Update the variable to test
    if variable == 1
        tau = k;
    else
        N_0 = k;
```

```
    end

    % Solve the characteristic equation
    [root, value, flags] = fsolve(@characEqPML, x_0, options);

    % Check the results of the solver
    if flags == 1 && real(root) < 0
        stableValues = [stableValues k];
    end
end

end
```

Listing A.7: characEqPML.m

```
function [F] = characEqPML(x)
%CHARACEQPML    Represent the characteristic equation of the power
    system
%with Power Management of Loads (PML). The shape of the characteristic
%equation is F(x) = 0. In this case, the variable x is the eigenvalue
    of
%the system.
%   [F] = CHARACEQPML(X)
%   I:  X   The value of the variable
%   O:  F   The value of the function F

% Parameters of the UPS
global D_l f_0 H S_B W_0

% Parameters of the PFC
global Delta_f_min p

% Variables of the PFC
global N_0 tau

% Ancillary parameter
C = f_0 / (2 * H * S_B + W_0);

% The characteristic equation
F = x + C / D_l - C * p * N_0 / Delta_f_min * exp(- tau * x);

end
```

A.3.2 Numerical simulation

Listing A.8: solvePML.m

```
function [t, f] = solvePML(dp_s_load, n_loads, time_delay)
%SOLVEPML   Solve the power system with Power Management of Loads (PML)
    as an
%DDE system.
%   [T,F] = SOLVEPML(DP_S_LOAD,NLOADS,TIME_DELAY)
%   I:  DP_S_LOAD   the constant system load power deviation     [MW]
%       N_LOADS     the thresold of aivalable loads              [loads]
```

```
%         TIME_DELAY   the constant time-delay                    [s]
%    O:   T            the time t                                 [s]
%         F            the system frequency                       [Hz]

% Parameters of the UPS
global D_l f_0 H S_B W_0
D_l = 1/80;       % the frequency dependency constant [Hz/MW]
f_0 = 50;         % the nominal frequency             [Hz]
H = 5;            % the total inertia constant        [s]
S_B = 4000;       % the total rating                  [MW]
W_0 = 100;        % the nominal kinetic energy        [MW/Hz]

% Parameters of the PML
global Delta_f_min Delta_f_max N_0 p tau
Delta_f_max = 0;     % the maximal threshold frequency deviation      [Hz]
Delta_f_min = -0.2;  % the minimal threshold frequency deviation      [Hz]
N_0 = n_loads;       % the number of available loads                  [loads]
p = 50e-6;           % the quantized load                             [MW]
tau = time_delay;    % the time constant of the turbine               [s]

% Inputs of the system
global Delta_P_m Delta_P_s_load
Delta_P_m = 0;                   % the mechanical power deviation     [MW]
Delta_P_s_load = dp_s_load;      % the system load power deviation    [MW]

% Solve the DDE system thanks to the DDE23 function
t0 = 0;           % the lower bound of integration    [s]
t_final = 30;     % the upper bound of integration    [s]
y0 = [0];         % the initial conditions            [Hz]
lag = [tau];      % the constant delay                [s]
options = ddeset(...
    'RelTol', 1e-3); % the relative error tolerance
[y_out] = dde23(@sysPML, lag, y0, [t0 t_final], options);

% Determine the output of the system
t = linspace(t0, t_final, 1000);      % the time
y = deval(y_out, t);                  % the frequency deviation
f = f_0 + y;                          % the system frequency

end
```

Listing A.9: sysPML.m

```
function [f] = sysPML(T, Y, Z)
%SYSPML Represent the DDE system of the power system with Power Management
%of Loads (PML).
%    [F] = SYSPML(T,Y,Z)
%    I:  T         the time t
%        Y(1)      the frequency deviation at time t
%        Z(1)      the frequency deviation at time t - tau
%    O:  f         the function f as y' = f(T, Y)
```

```
%         f(1)      the derivative of the frequency deviation at time t

% Parameters of the UPS
global D_l f_0 H S_B W_0

% Parameters of the PML
global p

% Inputs of the system
global Delta_P_m Delta_P_s_load

% Ancillary parameters
Delta_P_f_load = - allocationFunction(Z(1)) * p;
Delta_P_load = Delta_P_s_load + Delta_P_f_load;
Coef = f_0 * f_0 / (2 * (H * S_B + W_0));

% Compute the function f
f(1) = (Delta_P_m - Delta_P_load - Y(1) / D_l) * Coef / (f_0 + Y(1));
f = f';

end
```

Listing A.10: allocationFunction.m

```
function [n] = allocationFunction(Y)
% ALLOCATIONFUNCTION  Determine the number of quantized loads to switch
    off
% from the frequency deviation for a power system with Power Management
    of
% Loads (PML). The allocation function is a piecewise-defined function
% defined as a P-controller.
%    [N] = ALLOCATIONFUNCTION(Y)
%    I:  Y    the frequency deviation              [Hz]
%    O:  N    the number of quantized loads        [loads]

% Parameters of the PFC
global Delta_f_min Delta_f_max N_0

% Compute the number of quantized loads to switch off
if Y >= Delta_f_max
    n = 0;
elseif Y > Delta_f_min
    a = N_0 / (Delta_f_min - Delta_f_max);
    b = - Delta_f_max * a;
    n = a * Y + b;
else
    n = N_0;
end

end
```

A.4 Transmission System Operator's perspective

Listing A.11: solveI.m

```
function [t, f, dp_m] = solveI(dp_s_load, time_c, droop, n_loads, time_delay, df_min, df_max)
%SOLVEI   Solve the power system with Primary Frequency Control (PFC) with
%the integration of the Power Management of Loads (PML) as a DDE system.
%    [T,F,DP_M] = SOLVEI(DP_S_LOAD,TIME_C,DROOP,N_LOADS,TIME_DELAY,DF_MIN,DF_MAX)
%    I:  DP_S_LOAD    the constant load power deviation             [MW]
%        TIME_C       the time constant of the turbine              [s]
%        DROOP        the speed droop                               [Hz/MW]
%        N_LOADS      the thresold of aivalable loads               [loads]
%        TIME_DELAY   the constant time-delay                       [s]
%        DF_MIN       the minimal threshold frequency deviation     [Hz]
%        DF_MAX       the maximal threshold frequency deviation     [Hz]
%    O:  T            the time t                                    [s]
%        F            the system frequency                          [Hz]
%        DP_M         the mechanical power deviation                [MW]

% Parameters of the UPS
global D_l f_0 H S_B W_0
D_l = 1/80;      % the frequency dependency constant [Hz/MW]
f_0 = 50;        % the nominal frequency             [Hz]
H = 5;           % the total inertia constant        [s]
S_B = 4000;      % the total rating                  [MW]
W_0 = 100;       % the nominal kinetic energy        [MW/Hz]

% Parameters of the PFC
global S tau_t
S = droop;       % the speed droop characteristic    [Hz/MW]
tau_t = time_c;  % the time constant of the turbine  [s]

% Parameters of the PML
global Delta_f_min Delta_f_max N_0 p tau
Delta_f_max = df_max;    % the maximal threshold frequency deviation     [Hz]
Delta_f_min = df_min;    % the minimal threshold frequency deviation     [Hz]
N_0 = n_loads;           % the number of available loads                 [-]
p = 50e-6;               % the quantized load                            [MW]
tau = time_delay;        % the time-delay                                [s]

% Input of the system
global Delta_P_s_load
Delta_P_s_load = dp_s_load; % the system load power deviation            [MW]

% Solve the ODE system thanks to the ODE45 function
t0 = 0;          % the lower bound of integration    [s]
t_final = 30;    % the upper bound of integration    [s]
y0 = [0 0];      % the initial conditions            [Hz MW]
lag = [tau];     % the constant delay                [s]
```

```
options = odeset(...
    'RelTol', 1e-3); % the relative error tolerance
[y_out] = dde23(@sysI, lag, y0, [t0 t_final], options);

% Determine the output of the system
t = linspace(t0, t_final, 1000);    % the time
y = deval(y_out, t);                % (1,:) the frequency deviation
                                    % (2,:) the mechanical power deviation
f = f_0 + y(1,:);    % the system frequency
dp_m = y(2,:);       % the mechanical power deviation

end
```

Listing A.12: sysI.m

```
function [f] = sysI(T, Y, Z)
%SYSI Represent the DDE system of the power system with Primary Frequency
%Control (PFC) and and the integration of the Power Management of Loads
%(PML).
%    [F] = SYSPFC(T,Y,Z)
%    I:  T        the time t
%        Y(1)     the frequency deviation at time t
%        Y(2)     the mechanical power deviation at time t
%        Z(1)     the frequency deviation at time t - tau
%    O:  f        the function f as y' = f(T, Y)
%        f(1)     the derivative of the frequency deviation at time t
%        f(2)     the derivative of the mechanical power deviation at time t

% Parameters of the UPS
global D_l f_0 H S_B W_0

% Parameter of the PFC
global tau_t

% Parameters of the PML
global p

% Input of the system
global Delta_P_s_load

% Ancillary parameters
Delta_P_set_m = controlLoop(Y(1));
Delta_P_f_load = - allocationFunction(Z(1)) * p;
Delta_P_load = Delta_P_s_load + Delta_P_f_load;
Coef = f_0 * f_0 / (2 * (H * S_B + W_0));

% Compute the function f
f(1) = (Y(2) - Delta_P_load - Y(1) / D_l) * Coef / (f_0 + Y(1));
f(2) = (Delta_P_set_m - Y(2)) / tau_t;
f = f';

end
```

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