The Role of Inertia in Frequency Stability and The Implementation of Virtual Inertia in RES-based Power Plants

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

For economic and environmental reasons, the power system is changing. From having all the electric power production from large power plants based on fossil fuels to distributed generation based on renewable energy sources. This change results in a significant reduction in the system's inertia, challenging the existing frequency control. This work presents the frequency response of a three-area power system with two power plants based on renewable energy sources and a thermal power plant in order to study the role of inertia for frequency responses. Namely, the implementation of virtual inertia devices in the RES-based power plants is simulated and analysed to conclude about its impact on the power system. Namely, it will be determined that the virtual inertia devices will be vital for the power system evolution and for the increase of penetration level of RES-based power plants.

Keywords

Power System Control, Frequency Control, Virtual Inertia, Virtual Synchronous Generator.

Resumo

O sistema de energia elétrica está a mudar devido a motivações económicas e ambientais. Outrora, com a produção maioritáriamente proveniente de grandes centrais elétricas alimentadas por combustíveis fosseis, o sistema tem evoluído no sentido de integrar produção distribuída baseada em fontes de energia renováveis. Esta mudança resulta numa redução da inércia existente no sistema, desafiando o controlo de frequência existente. Este trabalho apresenta a resposta de frequência de um sistema de energia com três áreas, com dois pontos de geração baseados em energias renováveis e uma central térmica, com o objetivo de estudar a importância da inércia para as respostas de frequência do sistema. Nomeadamente, são implementados de dispositivos que apresentam inércia virtual nas centrais baseadas em energias renováveis para se simular, analisar e concluir acerca do seu impacto no sistema de energia. Será também determinada a importancia da inércia virtual para a evolução do sistema de energia, e para o aumento do nivel de penetração de energias renováveis.

Palavras Chave

Controlo do Sistema de Energia, Controlo de Frequência, Inércia Virtual, Gerador Síncrono Virtual

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Acronyms

AC	Alternating Current
DC	Direct Current
PV	Photovoltaic
DG	Distributed Generation
VI	Virtual Inertia
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine
SI	Synchronverter
RES	Renewable Energy Sources
ROCOF	Rate Of Change Of Frequency
PWM	Pulse Width Modulation

1

Introduction

Contents

1.1 Motivation and Problem Definition

Electricity has a large impact in nowadays' society. From small habitations to large manufacturing facilities, many daily life activities rely on the use of electric power. In order to be usable, the electric power delivered to the consumers must meet a certain power quality, mainly regarding voltage level, frequency and harmonic content. This will be only verified if the power system is operating as expected.

The electric power system can be divided into three main parts: the generating stations, the transmission system and the distribution system, [2]. The generation station is the place where the energy is converted from a natural form to electricity. The transmission system connects the generation areas to consumption areas. It operates at very high voltages to reduce the losses in this process. Finally, the distribution system takes the electric power from a transmission line to the individual customers.

Moreover, the need to operate such a large system while meeting the power quality requirements emphasises the importance of controlling the power system to keep its normal operation. The control can be divided into two major parts: the voltage level control and the frequency control.

One of the most significant limitations of electric power is that it cannot be stored in large amounts. It is not possible to produce the power previously to its consumption due to technological constraints which make it difficult, and economically not viable, to store large amounts of energy to consume later.

As it cannot be stored, all the power demanded in a given moment must be produced simultaneously. It should also be considered that the load demand changes every moment, so the production level must be adjusted accordingly. If there is a mismatch between the power produced and load demand power, the frequency will be affected [2]. Having two points on the grid with different frequency can cause the loss of synchronism between the two line ends. This will cause the disconnection of the transmission lines that could potentially affect several consumers, or even cause a blackout in an area. The frequency control aims to avoid these situations, keeping the power system operating with the load change, by adjusting the power production to the load demand in every instant.

Another issue addressed in this work is the evolution that is being observed in the electric grid. The power production was formerly generated in large power plants burning fossil fuels to create a rotation movement, providing mechanical power to the generator that would convert it to electrical power. Most of the power is still generated this way, however, there has been a growth of renewable energies. Motivated by the increasing of environmental concerns and technological evolution, new production solutions have emerged. These new energy generation methods have existed by over a century, but the recent increase in interest and investment in these methods presented viable alternatives to the classical generation methods.

With the new energy generation methods, new problems and challenges arose. As the energy production is based on renewable energy sources, its operation is fundamentally distinct from the classical generator's, introducing a new operation behaviour in the existing power system.

The classical power systems is an Alternating Current (AC) system operating at a given frequency, usually 50Hz or 60Hz. Being mostly powered by large synchronous machines, the power system's behaviour reflects these synchronous machines characteristics. Having a known behaviour, the power system control was based on its intrinsic characteristics. So, if there is a significant change in the system's behaviour, the whole power system control needs to be adapted and redesigned.

The renewable energy sources, such as solar or wind power, are not converted into electric power using a synchronous machine. Extracting power from the wind is mainly based on variable speed generators, which means variable frequency. In order to be injected in the grid, the power has to be converted to Direct Current (DC) and then converted to AC with a well-defined frequency. The conversion process decouples the power grid from the rotating machine, in this case, a wind turbine. The decoupling makes the wind turbine generator completely distinct from the classical synchronous generator from the grid standpoint of view.

The Photovoltaic (PV) technology, based on the interaction between two doped semiconductors, produces DC power which also has to be converted to AC using a DC-AC converter commonly known as an inverter [4]. The PV's operation does not rely on movement, presenting and operation principle fundamentally distinct from the synchronous generator's. On top of that, there is the operation of the converter, resulting in behaviour different from the classical generator.

It is not a matter of direct current being involved in the process, it is the completely different physical systems that are involved in the generation process. According to future prospects, the power system will have less and less rotating machines to generate power. There will be a lack of rotating masses that provide a unique behaviour specifically regarding damping and inertia.

With the increasing renewable energy penetration, [5], there is the risk that the main behaviour of the power system changes significantly. Currently, the control system of the grid is based on the synchronous machines' characteristics. Therefore, a significant change in the power system response can trigger uncertain events. It can even create new, yet unknown, events that can negatively affect the power system operation.

However, it is undeniable that the inclusion of these new energy sources is extremely important, especially for environmental and economic reasons, [4]. So, a solution for their inclusion in the existing power system must be found. Given that the power system control is dimensioned for its classical generators and their characteristics there are two possible approaches: adapt all the existing control devices and techniques to the new inverter-based technology behaviour, or control the new inverters in a way to simulate synchronous behaviour.

The solution for a smooth grid evolution is probably to keep using the existing control systems. Some of these techniques have been tested and applied for over a century. It has been operating and improved over time. So, it can also ensure one of the most important characteristics of the power system: reliability.

Emulating the well known synchronous machine behaviour on the inverter-based technologies will make its control extremely reliable and it will perfectly fit the existing power system.

1.2 Objective

This work aims to study the effects caused by the high penetration level of Renewable Energy Sources (RES). Namely, how this change on the power grid can influence the power system's frequency and what is the role that inertia plays in the frequency response when facing external perturbations. The installation of virtual inertia in power plants based on RES will also be the part of the main scope of the work, as it allows us to further understand the importance of the inertia in the power system.

In order to study the role of virtual inertia, a model of three interconnected areas will be modelled. The three areas consist in an area constituted by a thermal power plant, with a classical generator operating, and load, the second area has a wind park as well as its load, and finally, the third area has a PV power plant and also a load.

The area 1 is the central area and is connected to both other areas 2 and 3, which will be described later. The area's connection, established through transmission lines, allows the electric power to flow from one area to another, enabling compensation between areas.

The developed model should represent as accurately as possible the system described above while keeping analytical simplicity. The area 1 model should represent the operation of a thermal power plant connected to a load and two other areas. The areas 2 and 3 models should represent the operation virtual inertia device built-in the power plant based on wind and PV, respectively, as well as its loads and connections to area 1.

Once the model is developed, it will be implemented as a MATLAB program to produce simulation results. The program enables the simulation of different perturbations and outputs figures representing not only the frequency behaviour in the three areas but also the power exchanged between them.

Having the system's frequency responses to different perturbations makes it possible to analyse, with a significant level of detail, what happens in the system and what variables contribute to each part of the system behaviour. Therefore, it will possible to analyse the role of the virtual inertia on the system and to draw conclusions from it.

1.3 Outline

The outline of the thesis is as follows:

- Chapter 2 - The second chapter is dedicated to the previous work developed by different authors regarding the subject under study. Initially, the literature review is presented citing multiple works.

Next, the theoretical background is presented elaborating on the basic concepts applied throughout the thesis. Finally, the model of the desired system is presented.

- Chapter 3 - The third chapter is dedicated to the methodology used to analyse the three-area model. It also explains how the simulated results are obtained, as well as the reasoning behind each constant value.
- Chapter 4 - The fourth chapter includes not only the figures representing the simulation results but also the analysis of the phenomena occurring in each simulation.
- Chapter 5 - The thesis ends with the conclusions from the developed work.

2

Previous work

Contents

2.1 Literature Review

2.1.1 The Power System Evolution

For economic, technical and environmental reasons, the share of inverter-based generators is growing and is foreseen further growth. From large-scale power plants to small distributed generation points the penetration level of these new generation methodologies is increasing [6]. Whether these new generation units are based on solar energy, using the photovoltaic technology, on the wind power its behaviour will, typically, be different from the synchronous generator.

Different behaviour does not necessarily mean negative implications. However, the lack of inertia of the renewable sources power plants, based on power electronics, brings ”odd transient dynamics”, from the grid operation and control standpoint of view [5]. With a small level of penetration of the inverter-based technologies to produce electric power, these effects would be neglectable. However, with the increasing penetration level of renewable technologies, this effect must be taken into account and must be addressed.

The lack of physical inertia affects mainly the frequency because the inertia counteracts any frequency variations [7]. This is a desirable effect given that it reduces the frequency oscillations, keeping it closer to the desired frequency value, its rated value. In the classical synchronous generator, the inertia is inherent to its mode of operation. A physical rotating mass, in this case, the rotor, will always present inertia to the change of its rotating state. Therefore, it would be desirable if the inverter-based technologies could present similar behaviour.

2.1.2 Distributed Generation

Some authors have studied the effects of Distributed Generation (DG) in the power system, [8] and [9]. The authors identified not only the advantages and disadvantages of introducing distributed generation but also the impact that different penetration levels of DG can have on the power system, namely on the frequency.

The two main advantages of distributed generation are the reduction of greenhouse gases emission and the reduction of power losses in transmission lines, [8]. The first advantage comes from the fact that the distributed generation is based on renewable energy sources. The second advantage is justified by the fact that distributed generation, by definition, means power production near the consumer load. Therefore, the power produced does not have to be transmitted over long transmission lines, reducing the power losses.

However, the introduction of the distributed generation also originates negative effects on the network, creating stability problems and operation and control issues, [8], as the main behaviour of the system will be affected. These issues are more relevant as the DG's penetration level increases, [8], so these concerns must be taken into account to operate the power system.

Another study regarding the penetration level presents interesting results, [9]. The authors studied the influence of different DG's penetration level on a 8-bus system and 39-bus system. The simulation results showed that when having over 55% of DG's penetration level on the system could cause frequency instability when faced with a perturbation such as a short-circuit on one of the lines. This simulation considers that the distributed generation units have no inertia to contribute to the frequency stability, causing the frequency to collapse.

As final conclusions, the authors, [9], suggested that to have a high level of penetration of distributed generation while keeping the system stability, some energy compensation means should be introduced. For example, adding energy storage systems to the distributed generation units could increase the maximum connection capacity while keeping frequency stability. There are also other ways of introducing this energy compensation through inertia response which will be explored later in this text.

2.1.3 The Proposed Solution

The proposed solution by many literature sources, which will be explored and analysed throughout this work, consists in making the converter-based power plants contribute with inertia to the frequency perturbations in the power system. As the power plants based on renewable energy sources are converter-based, having a solution that makes possible these power plants behave as the classical synchronous generators would simplify the introduction of RES.

The studied idea to implement this principle consists in the emulation of the desired behaviour of a synchronous generator implemented in the control layers of the power electronics [5]. Controlling the inverter operation will allow manipulating the behaviour of the power plant, seen from the external side. This method will shape the inverter-based technologies in a way that from the outside control point of view it will be the same as the classical synchronous generator, emulating the inertia and the damping nature.

Once the classical generator's behaviour is mimicked by simulating the desired parameters, the inverter-based power plants will also contribute to the power system's operation counteracting the frequency perturbations. For example, a PV power plant will also have inertia, that, even not being a physical parameter, will help to decrease frequency variations when there is a load demand change.

With different research groups working on the subject, different solution's implementations have emerged. Based on the same concept, the virtual inertia, the various solutions present distinct advantages and disadvantages which should be taken into account for the desired application.

A wide study of the existing literature regarding electrical converters with virtual inertia capabilities was developed in 2019, [10]. The authors analysed several articles from different research teams, identifying the similarities and differences from the distinct solutions. These works separate the virtual inertia based converters in three types: the Virtual Synchronous Generator (VSG), the Virtual Synchronous Machine (VSM), and Synchronverter (SI).

The virtual synchronous generator is based on conventional inverter hardware controlled in a way that emulates the energy release and absorption. This behaviour allows the converter to counteract the system frequency perturbations once they are detected. The main advantages of this topology are its simple implementation and the capacity of changing the parameter values of the inertia constant, H, and damping factor, D, which are explained in the following section [10].

The virtual synchronous machine is based on the emulation of the synchronous machine making use of the Park transformation increasing the response time when compared to the alternatives. On the other hand, the VSM presents a higher range of inertia constant values [10].

Finally, the synchronverter is an inverter with a control algorithm which mimics the behaviour of a synchronous machine. In general, it is equivalent to a synchronous machine connected to a capacitor bank [10].

Naturally, all the different implementations described previously are much more complex than described. However, a complete description of these implementations will not be discussed in this work, mainly for two reasons. Firstly, the detailed functioning of the converter's new technology is out of the scope of this work. Secondly, due to the economic and academic importance of this topic, the researchers do not provide a lot of detail about their implementations.

Having identified possible solutions to introduce virtual inertia in the power system, it is important to study the implementation of this technology to physical systems. Therefore, the results from implementations developed by different sources will be analysed in the next sub-sections.

2.1.4 The VSYNC Project

The VSYNC project, developed between January 2007 and December 2010, aims to implement a virtual inertia system in a real operating power system. This European project had various participants such as the Delft University of Technology and the University Politehnica of Bucharest being led by the Energy Research Centre of the Netherlands, producing research articles, [11–18], that support the utilization of virtual inertia technologies to improve power system's stability.

In one of the articles produced during the project, the authors start by briefly describing the concept of the virtual inertia and how the virtual synchronous generator should interact with the operating grid, as presented in figure 2.1, [1]. This article also enhances a very important aspect of the operation of a virtual synchronous generator, namely the physical system that will be able to emulate the inertial response desired. It also proposes to use an energy storage device that will be able to both inject and absorb energy from the grid. This approach allows the system to always operate at the maximum value of power production, requiring a higher initial investment to purchase the energy storage equipment.

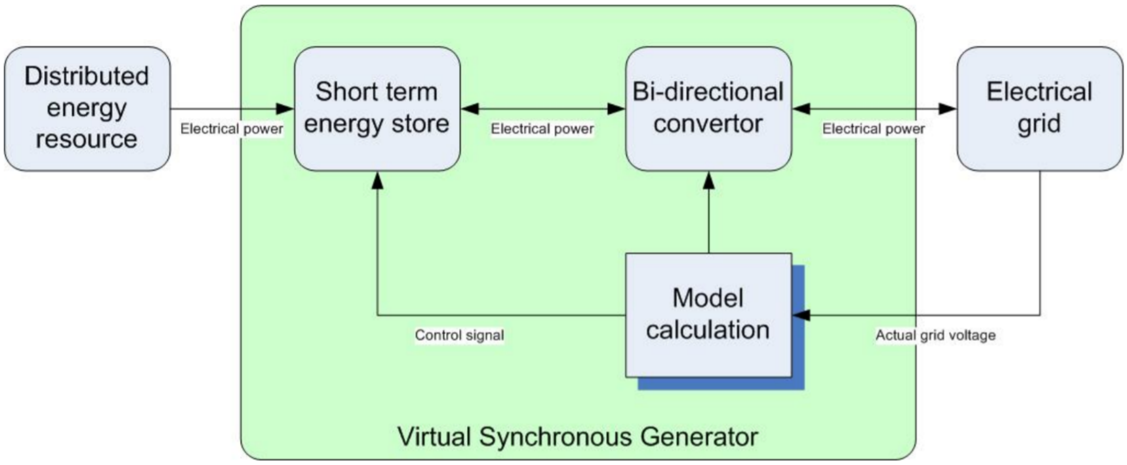

Figure 2.1: Principle of Operation of a Virtual Synchronous Generator [1]

Some practical results from the VSYNC project were presented and discussed, [19], testing a virtual synchronous generator operation in the real electric system in Cheia, Romania. This VSG consisted of a flywheel connected to electric converters that allowed the energy storage device to emulate virtual inertia by injecting and absorbing energy from the grid. The energy exchange between the VSG will then affect the frequency, improving the system stability.

The authors also presented promising results, as the virtual synchronous generator was able to compensate for the perturbations in the frequency, [19]. These results led to the authors' conclusion that the tested technology, the VSG, presents an operational solution to compensate for the increasing share of distributed generation in the electric power system. The authors also concluded that the VSG may play an important role in the future grid.

The VSYNC project highlights that many relevant European entities are interested in developing the virtual synchronous generator technology, as well as implementing it in real power systems. However, this study does not present an implementation of Virtual Inertia (VI) directly tied to a power plant based on renewable energy sources, which are presented in the following sub-section.

2.1.5 Virtual Inertia Applied to PV Power Plants

Published in 2013, [5], aims to model a PV power plant, emulating the synchronous generator behaviour while feeding a load, along with a traditional synchronous machine. It also evaluates the response of the system described earlier in an islanded mode, without outside compensation, showing that it is possible to keep the load demand fed, even during and islanding mode.

The article, [5], is especially important because it models the PV power plant, that uses the usual DC-DC converter to step up the voltage level, followed by an inverter to convert the power to AC, as a synchronous generator, and in the form of a transfer function. The transfer function presents the desired parameters, inertia and damping factor, which can be tuned. The contact between the transfer function emulating the synchronous behaviour and the inverter is established through the control of the Pulse Width Modulation (PWM) that guides the inverter functioning.

In 2015, an article presenting an aggregated model of a PV powerplant with a rated power of 1 MW and constituted by 20 power converters was presented [7]. It aims to model the large power plant based on an equivalent model of the developed models for lower power capacities. After simulating the response of 20 different units connected with the equivalent model to all the units together, an error bellow 1% was obtained, proving that whole large PV power plants could be modelled as one synchronous generating, allowing inertia to be emulated.

All the articles referred above, [6], [7] and [5] show important principles that will be used in the modelling of the system under study on this work. Namely, the concept of controlling a PV power plant as an emulation of a synchronous machine [6]; the representation of the virtual synchronous generator as a transfer function, and its parameter flexibility [5]; and, finally, the modelling of a large capacity PV power plants as one equivalent of many smaller units, [7], that enables a simpler analysis to large-scale problems.

2.1.6 Virtual Inertia Applied to Wind Power plants

The wind penetration increase has also been a topic of interest for studies like [20] that tests how the power system from the Republic of Ireland will respond to this change. As it is a small system, its inertia is vital to keep its frequency stability. So, the authors compared the frequency response to perturbations on the system with some wind turbines not having inertial response. The variable speed wind turbines do not inherently contribute to the inertial response, due to the fact that the rotor is decoupled from the power system, [20].

From the simulated Irish power system the authors, [20], concluded that if the wind turbine generators do not contribute with an inertial response, the frequency will drop lower during times of low demand, which could be problematic for the system frequency stability. However, when the wind turbine generators included an inertial response the system response was smoother and similar to the response without any wind generation. These results show that if the generation units based on renewable energy sources are operated in a way to emulate the inertial response they could replace the conventional generation methods without compromising the system stability.

Other studies, such as [21], are also based on the concern that variable speed wind turbines need to be operated, or controlled, in a way that the wind farms contribute to the frequency stability through the inertial response.

In [21], the authors modelled a 15 MW wind farm connected to the grid. Then, a load increase was simulated and the frequency response was obtained. This simulation experiment was repeated with no inertial contribution from the wind farm and with two distinct implementations of virtual inertia. As expected, when the wind farm had no virtual inertia the frequency dropped to a lower value.

Both studies highlight the importance of virtual inertia from wind power plants for frequency stability. They also reveal that virtual inertia technology is already under research and it may be widely implemented due to its advantages to the power system stability.

2.1.7 Literature Research Conclusions

From the vast selection of articles presented throughout this section three main conclusions can be taken for this work. Firstly, to keep the power system's frequency stable, while increasing the penetration level of renewable energy sources, it is necessary to mimic the behaviour of the classical synchronous generator.

The second main conclusion is that there are already devices under study and test which can emulate the synchronous generator behaviour by having virtual inertia. These devices will make a renewable energy source power plant indistinguishable from the grid standpoint of view. The final conclusion is that the implementation of VSG has already been tested in both PV and wind solutions, presenting promising results.

The presented conclusions enhance how relevant the implementation of virtual inertia systems can be, in the near future, for the power system's operation. Therefore, this work lays on the foundations of the previous works, taking the new models of VSG and studying its frequency response, when integrated into a 3-area power system.

2.2 Theoretical Background

In order to study the three interconnected areas system response to frequency perturbations, it is necessary to define a model not only for total system but also for its individual components. Each individual component's model will be based on well known established equations that relate the variables of interest for each component. The models will be defined from a transfer function standpoint of view, characterising the relationship between the inputs and output in each component in the Laplace domain.

The following subsections describe how the models for each part of the different power plant were obtained, and how they can be combined into the final system. In addition, the approximations that were made in order to simplify the studied problem will be identified and explained.

2.2.1 Steam Power Plant Model

A steam power plant can be described by its four main components: the governor, the turbine, the generator and the load. The governor controls the gate/valve opening, hence controlling the steam flux into the turbine. This will affect the turbine's mechanical power output, P_m, and the mechanical torque, T_m. The mechanical power is transferred to the generator through the shaft, and the generator converts the mechanical power to electric power, P_e that will be consumed by the load [2].

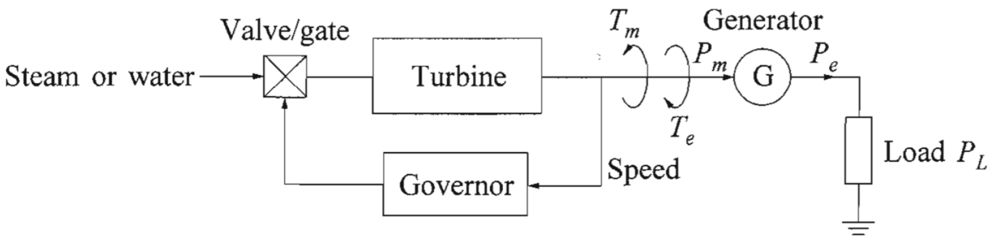

Figure 2.2: Turbine-based power plant scheme [2]

The voltage frequency output of the generator is naturally related to the rotating speed of its rotor which is related to the difference between mechanical and electric torques as,

$$2H\frac{d\omega_r}{dt} = T_m - T_e, \tag{2.1}$$

where ω_r is the angular velocity of the rotor in pu, and H is the inertia constant [2].

A load variation will change the value of the electric torque, as the load will demand a different amount of power. This will create a mismatch between the mechanical and electric torques, which will result in a rotor velocity change and consequently a frequency variation. By analysing 2.1 one can also say that the larger the value of the inertia constant, H, the lower variation in the frequency, suggesting that a high inertia value is advantageous to keep low frequency variations and, therefore, the system stability.

The diagram that represents the transfer function that relates the torques and the speed variation, based on 2.1, is as depicted in 2.3 in its Laplace transform form.

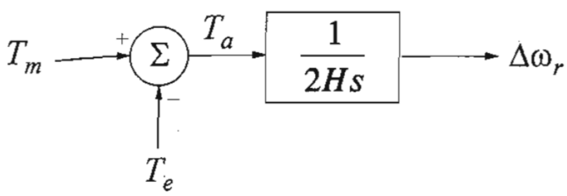

Figure 2.3: Block diagram relating the torques and frequency variation [2]

However, it is preferable to express the frequency variation as a function of powers, electrical and mechanical, instead of torques. This will allow the model to emphasize the effect that power variations have on frequency variations, which is the main scope of this study. The expression that relates this two variables, in load-frequency studies, is given by

$$P = \omega_r T. \tag{2.2}$$

In control problems, it is usual to represent the variables as a sum of its steady-state value with a small deviation [2]. The suffix "$_0$" suffix represents the steady-state value and the "Δ" represents the small deviation of the variable. So,

$$P = P_0 + \Delta P, \tag{2.3}$$

$$T = T_0 + \Delta T, \tag{2.4}$$

$$\omega_r = \omega_0 + \Delta\omega_r. \tag{2.5}$$

Now, it is possible to write 2.2 as

$$P_0 + \Delta P = (\omega_0 + \Delta\omega_r)(T_0 + \Delta T). \tag{2.6}$$

Considering only the small deviation terms we obtain

$$\Delta P = \omega_0 \Delta T + T_0 \Delta\omega_r. \tag{2.7}$$

Given that the power and torque deviations are expressed by the difference of their mechanical and electrical components:

$$\Delta P_m - \Delta P_e = \omega_0(\Delta T_m - \Delta T_e) + (T_{m0} - T_{e0})\Delta\omega_r. \tag{2.8}$$

In the steady-state the mechanical and electric torques are equal, making its difference equal to 0. Also, the rotor speed in this condition is equal to 1 pu. So, from 2.8 we obtain

$$\Delta P_m - \Delta P_e = \Delta T_m - \Delta T_e. \tag{2.9}$$

From 2.9 it is possible to establish the transfer function relating speed and power.

Where M is a more compact way of writing 2H. Analysing the obtained model one can say that the speed variation will depend on the miss-match between the mechanical power and the electric power.

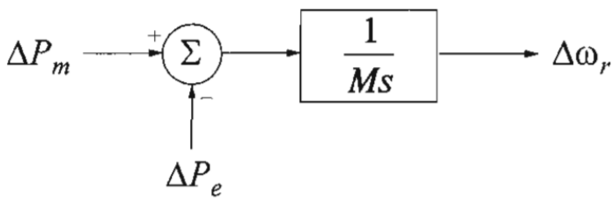

Figure 2.4: Block diagram relating the powers and speed variation [2]

2.2.2 Load Model

The load should also be modelled in order to reflect its effect on frequency deviation. For the subject under analysis it is important to know that the power system's loads can be divided into frequency-dependent loads, and non-frequency dependent loads [2]. The power consumption by resistive loads does not depend on the frequency. However, the motor loads are sensitive to frequency because it changes the rotor speed, changing the operating power of the motor.

In order to characterise the load behaviour, we should introduce the damping factor, D, which represents the load sensitivity with respect to frequency. Meaning that if the load-damping factor, D, is equal to 2, a 1% change in frequency translates into a 2% change on the load power. This factor can be written as,

$$\Delta P_e = \Delta P_L - D\Delta\omega_r, \tag{2.10}$$

where ΔP_L represents the non-frequency-sensitive load change, and Dω_r represents the frequency-sensitive load change.

Given the relationship between the electric power and rotor speed evident in 2.10, an updated transfer function, containing the load-damping factor, D, can be written and represented as

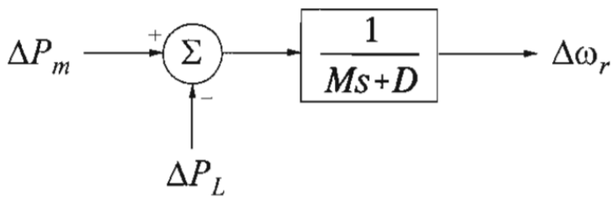

Figure 2.5: Block diagram relating the load and frequency variations [2]

Analysing the obtained transfer function one can say that the response to a frequency deviation depends on the generator's inertia, and on the load sensitivity with respect to frequency.

2.2.3 Governor Model

The governor is also an extremely important component of the power plant. It regulates the turbine input, and consequently its torque and mechanical power output, which plays an important role in the system. Naturally, the governor's operation will have as an input the speed variation, which comes as feedback from the system's output, namely the frequency or system speed. Therefore, the governor can act on the valve opening, reacting to the speed deviations verified. It can be represented as

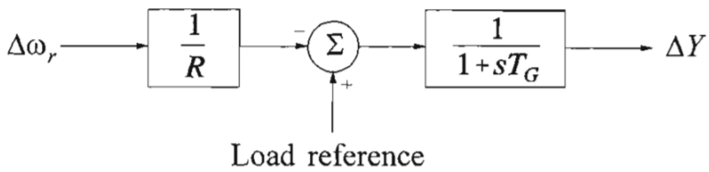

Figure 2.6: Block diagram representing governor behaviour [2].

The governor output is connected to the valve control input, before the turbine output. The governor time constant, T_G, is much smaller than the other time constants that are involved in the system, and, in general, the system time response is determined by the poles with the higher time constant values [22]. Considering this fact and in order to simplify the final system model, the governor time constant, T_G, will be neglected. Also, a proportional gain will be added before the signal arrives to the valve, and will be represented as $\frac{1}{\sigma}$. With the referred changes the obtained transfer function is as represented in figure 2.7.

The variable R is described as speed regulation and its value determines the ratio of frequency or speed variation with respect to the change in valve or gate position, or mechanical power output, which can be represented as

$$R = \frac{\Delta\omega}{\Delta Y} = \frac{\Delta f}{\Delta P}. \tag{2.11}$$

So, the inverse of R, $\frac{1}{R}$, represents the change in the turbine's power output with respect to the frequency variation. For example, if R has a value of 0.02, or 2%, its inverse $1/R$ is 50, which means that a 50% power variation translates into a 1% frequency variation.

Using this model for the governor means that no delay introduced by the device is considered. Also, the governor will operate as feedback, taking the frequency variation at the output of the generator, and based on its value and on the load demand, change the valve opening, to keep the power system

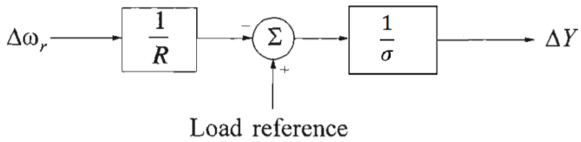

Figure 2.7: Block diagram representing governor behaviour.

operating.

2.2.4 Steam Turbine Model

A steam turbine is an extremely complex machine, it is a multi-order system on its own due to its complexity. However, to include a turbine model that should be only a small part of the system we should consider a very simplified model. However, there are simplified models described in the existing literature, such as in [2], that describes the steam turbine, non-reheat, as a single-pole, as represented in figure 2.8.

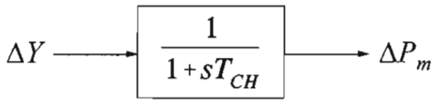

Figure 2.8: Block diagram representing turbine behaviour [2].

This transfer function models the turbine as a simple delay between the received signal from the governor and the power output. It is clearly a simplification of the turbine machine.

However, given the dimension of the system under study and considering that the presented simplified model only represents a delay between the vale opening and the mechanical power output, the effect will be neglected in the final model of the steam-based power plant. Even while using a simplified model it gives us an approximation of its real behaviour.

2.2.5 Steam Power Plant Model

Combining the governor, the generator, and load models, a steam turbine power plant model will be obtained. Naturally, the governor will take the speed variation signal, and based on that it will take an action in the valve feeding the turbine. The turbine will operate with the steam allowed by the given valve opening, outputting a mechanical torque. The shaft connecting the turbine and the generator where the electric power is produced in order to meet the load demand. A load change affects the governor behaviour, changing the whole process that takes place forwards. The described behaviour can be understood by analysing the diagram represented in figure 2.9.

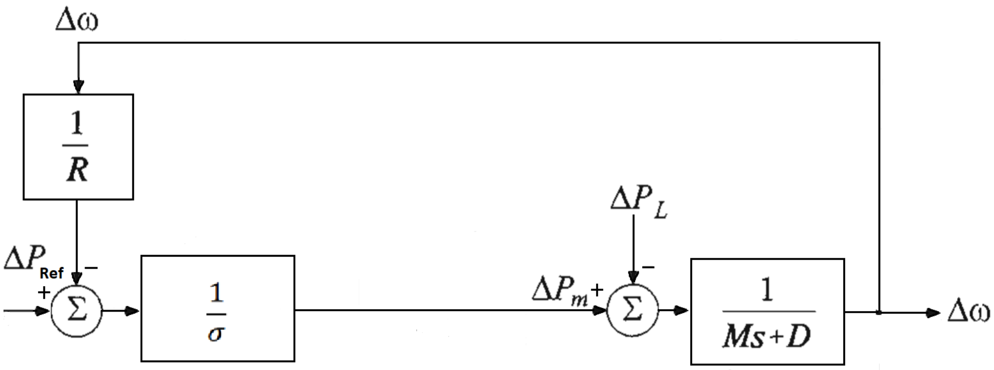

Figure 2.9: Block diagram for the steam power plant.

In 2.9, the variable P_{ref} represents the reference power which determines the amount of power that the power plant should be output. Naturally, the value of this variable varies and its variation will depend on the frequency values, so one can affirm that this variable represents a feedback loop acting on frequency changes. In order to keep the figure simple, and as it is not the focus of this study, the control system that determines the reference power, P_{ref}, is omitted and is not considered in this work.

The obtained model is an interesting representation of the plant, making possible to study its behaviour with perturbations. Namely, the effect of power productions or load power variations on the frequency. However, in order to fully complete the desired model with three areas extra blocks should be added. These will be obtained and described in the next section.

2.2.6 Photovoltaic Power Plant and Wind Park model

The main scope of this work aims to study the role of inertia for the frequency response from power plants whose operation does not inherently present inertia. For a renewable energy source-based power plant, such as a photovoltaic unit or a wind park, to present an inertial response, a device that emulates virtual inertia is required.

The wind turbines, having rotating components, have inertia built-in, however, it is decoupled from the electric grid through electrical converters. So even the wind turbine parks need the addition of some inertia to contribute to the system's stability.

The device under study that emulates the virtual inertia is known as Virtual Synchronous Generator and it is assumed to be present in both renewable sources power plants. Hence, the two power plants which are completely different from a physical functioning standpoint of view will present an identical model for this study.

Also, the simulations will test the frequency variation responses to power variation perturbations. So, the model that is interesting for this purpose is, naturally, a model that relates the power and frequency variations. This will make the model for this power plants to be heavily based on the virtual synchronous generator because that is the device that will relate the two variables under analysis, and the effect that is aimed to be studied.

The model presented in 2.10 depicts the block diagram of the virtual synchronous generator control which will be used to model the photovoltaic power plant and the wind park. It was inspired in [3], which describes a complete model for VSG, even detailing how the reference signals are generated. Such level of detail is out of the scope of this work, so the simplified version depicted in 2.10 will be a good approximation to keep model simplicity while representing the operation of the device.

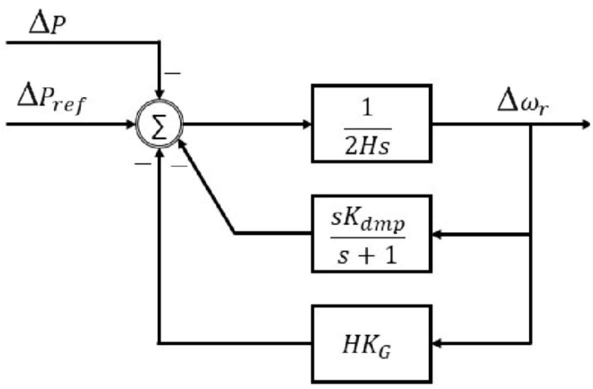

Figure 2.10: Block diagram for the voltage synchronous generator [3]

Similarly to the steam-based power plant, the input signal P_{ref} represents the power value that the power plant should be outputting. Naturally, it is computed by other devices based on the frequency, so it is like feedback that counteracts the frequency deviations.

The variable H represents the virtual inertia constant, which is emulated to mimic the behaviour of the classical physical generators. The variables K_G and K_{dmp} are the droop coefficient and damping coefficient respectively. The value of H determines the capacity that the power plant has to respond to frequency perturbations, while the values of K_G and K_{dmp} should be tuned by trial and error.

An important point to bear in mind is that the virtual inertia requires a physical expression in order to affect the real physical power system. The so-called inertia refers to the capacity to inject, or absorb, energy from the grid, counter-acting its changes in frequency, in an integrative way. So the virtual synchronous generator requires a mean to implement such operations in order to operate as desired. There are two main approaches to physically implement the emulated inertia, which will be described in the next paragraphs.

The first approach, described by the majority of the literature dedicated to virtual inertia, is the use of an energy storage device. Many different technologies can be used to store energy, such as flywheels, batteries with different chemical compositions, and even supercapacitor, even tho this last technology cannot store large amounts of energy, it can present a fast power contribution, which is also important to control the system response. It is important to take into account that if this is the method used, the storage devices' state of charge should never be too high or too low, to allow flexibility in the operation to either inject or absorb power from the grid.

The second approach consists in reducing total power output, allowing a margin to increase the power injection, emulating the inertial response. For example, if the maximum power that a photovoltaic power plant can produce 100 MW, the power plant will only operate at 90% of the maximum capacity in order to be able to inject the extra power in the grid to emulate the inertia.

In order to determine which of the two approaches should be used, an economic assessment should be performed. Naturally, the optimal solution may vary from case to case and might even change along with technological advances, namely in the energy storage industry.

It should be taken into account that the physical systems that will emulate the inertia also introduce effects on the system and those effects are not being taken into account. It should also be noticed that control theory requires linear models to be effective. Therefore, no saturation is considered for the control design, it only appears in the simulations. Even with all its limitations, the obtained model should be detailed enough to provide accurate results while keeping the model simplicity.

2.2.7 Two interconnected areas model

In order to connect two generation areas, there must be a connection link. The connection link that will be used is a transmission line, that will establish the connection between the two areas. The addition of this component will allow power to flow from area 1 to area 2 or vice versa, which is extremely useful to ensure the power system stability and smooth operation. Having only one area means that this area must be able to meet the load demand on its own, without external influence. With the two connected areas, one area may compensate for the perturbations that occurred in the other area, putting less stress into a single generation area.

The transmission line that will establish the link must be modelled and added to the model developed to this point. As it is usual, the line will be modelled as a reactance between the two areas, so the power flowing in the line will depend on the angle, δ difference in the two ends of the line, as

$$\Delta P_{12} = \frac{E_1 E_2}{X_T} sin(\Delta\delta_1 - \Delta\delta_2), \tag{2.12}$$

where E_1 and E_2 are the voltage magnitudes in area 1 and 2 respectively, and X_T is the value of the transmission line reactance. However, this equation is not linear so it has to be linearised [2]. As the argument difference is small, and that the magnitude in both areas is the rated value (1 pu), the expression can be written as

$$\Delta P_{12} = \frac{1}{X_T}(\Delta\delta_1 - \Delta\delta_2). \quad (2.13)$$

Including the transmission line to connect two areas modelled earlier, the following block diagram is obtained. The model represented in 2.11 reflects the behaviour of two steam turbines.

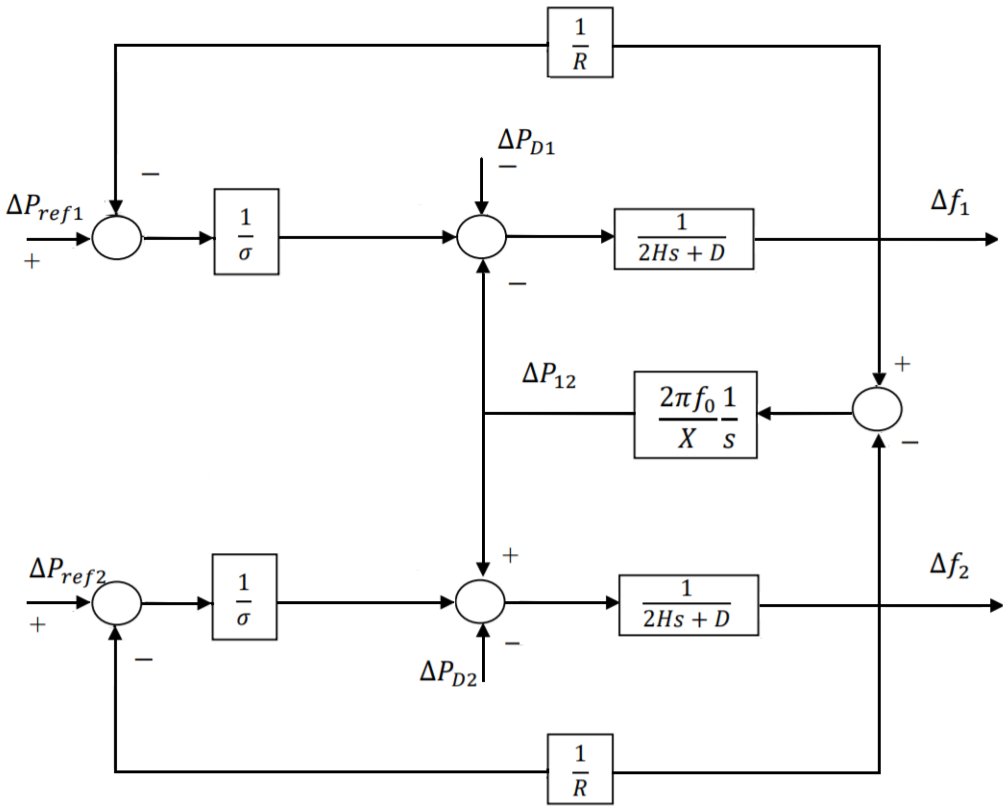

Figure 2.11: Two interconnected areas block diagram.

The block diagram representation in 2.11 considers both areas equal, with the same parameters. However this may or may not be the case, the model is valid for both situations, once the needed parameter adaptations are made. It is also possible to connect two areas that produce electric power from different sources, as long as the respective transfer functions are adjusted to represent the real differences.

Naturally, the theory presented here to interconnect two areas can be extrapolated to connect three or more areas. The only difference will be the dimension of the modelled system and the number of transmission lines, which can have different parameters.

2.2.8 Three interconnected areas model

In this subsection, the models for each kind of power plants presented earlier will be combined in order to build a model for the three areas that will be studied under various simulated disturbances. The system that is aimed to be modelled consists in three power plants: a classical thermal power plant based on a steam turbine, a wind park that is operating with a virtual synchronous generator, and, a solar power plant also operating with a virtual synchronous generator.

The areas are interconnected in a way that the thermal power plant, area 1, is connected through a transmission line to both areas based on renewable energy sources, 2.12. So the area 1 assumes a central position having a direct connection with the other areas. The rationale behind this connection arrangement is that the system that the large thermal power plant should be farm from large electricity consumption centre, so transmission lines with the capacity to transmit large amounts of power should link the production area to the consumers. The other two areas are not connected to each other because they represent the renewable energy power plants closer to the consumption areas.

This model set up allows not only to simulate load variations in all the three areas but also to simulate the loss of line connection or production variation, allowing high simulation flexibility.

Throughout this chapter, the model of the system under study, the 3-area system, was presented. Next, it is necessary to define the used methodology that will allow obtaining simulation results, which are the ultimate goal of this work. The approach to the system and mathematical operations to obtain the simulated results will be presented and explained in the following chapter.

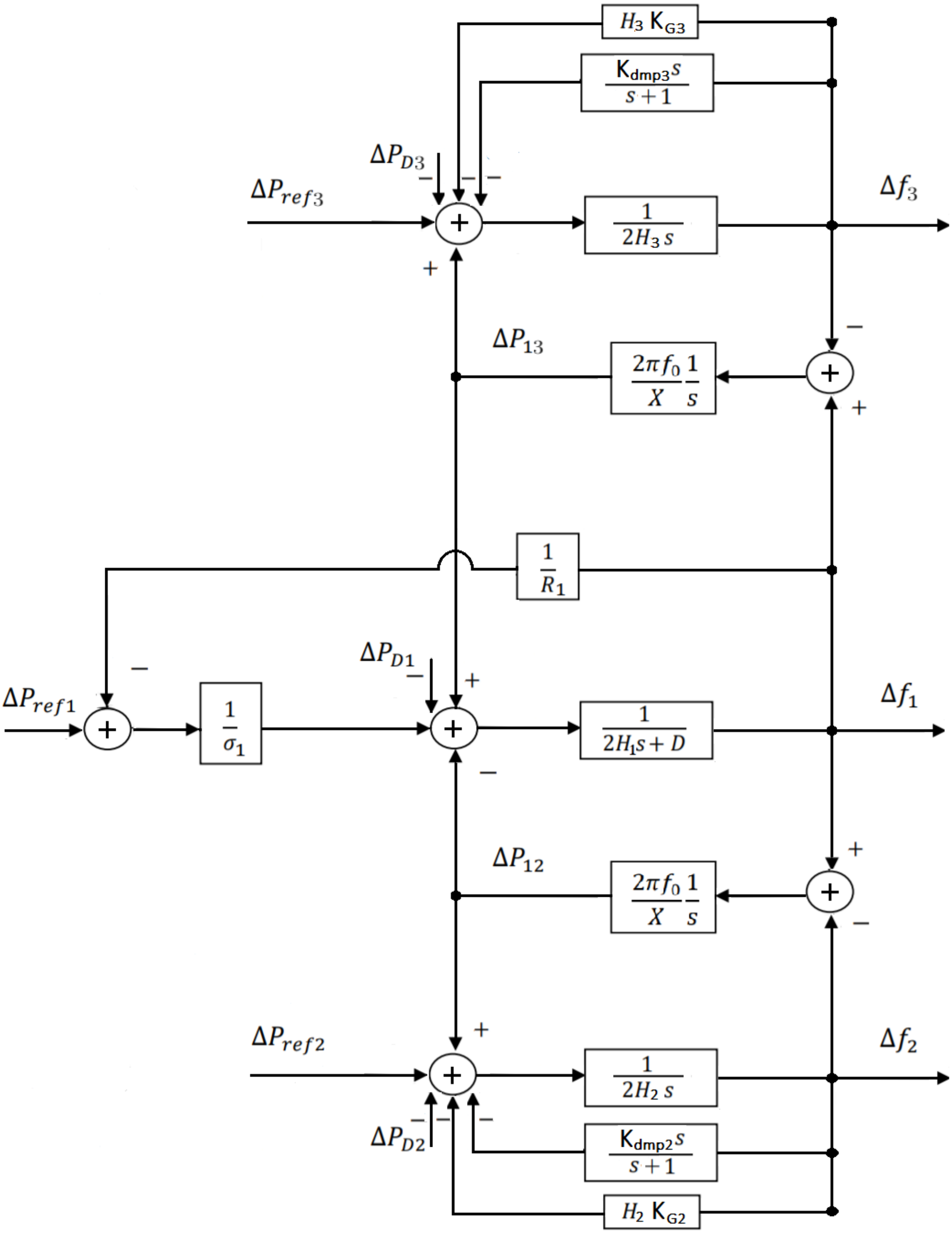

Figure 2.12: Three interconnected areas block diagram.

3

Methods

Contents

In this section, the methods applied to obtain the simulation results will be presented and explained. Namely, the state model approach and the main equations that represent the three-area system and the methodology used in order to simulated system perturbations and its response.

3.1 State Model Representation

In order to obtain simulation results from the three-area model, the problem was approached from a state model representation standpoint of view. This representation usually follows the form of linear differential equation, the famous state equation:

$$\dot{x} = Ax + Bu. \tag{3.1}$$

Where x represents the vector containing the state variables, $\dot{x}$ is the vector with the first-order derivative of the state variables, u is the control vector, A is the state the matrix and B is the input matrix. The state variables are the variables that describe the model state and naturally, as the state equation shows, its value depends on other variables. The control variables are the variables that can be operated to control the system. So, one operates the control variables in order to get to a desired value for the state variables.

In order to differentiate another variable topology, another term will be added to 3.1. The new term p will represent the perturbation variables, which are variables that affect the value of the state variables, however those are external inputs. The matrix Γ will represent the connection between the perturbation variables and the state variables.

The perturbation variables could be classified as control variables, however, it makes sense to establish a clear difference between the two given that the control variables, as the name suggests, belong to the control space, and the perturbation variables will represent external inputs which will introduce perturbations to the system. Hence, the equation that describes the model is given by

$$\dot{x} = Ax + Bu + \Gamma p. \tag{3.2}$$

The presented state equations naturally describe differential equations, in the time domain whose equivalent in the s-domain are present in the model for the three-area model depicted in 2.12.

3.2 State Model Representation Applied to the three-area model

Analysing the block diagram of the three are system, represented in 2.12, and knowing the study that is intended to be done, one can identify the state model classification of each variable. The state variables will the frequencies in each area and the power that is transmitted between areas, namely Δf_1, Δf_2, Δf_3, ΔP_{12} and ΔP_{13}. Knowing how this variables behave facing a perturbation will allow us to define the state of the system and understand how it is behaving. So, the state variable vector used along this work is defined as:

$$x = \begin{bmatrix} \Delta f_1 \\ \Delta f_2 \\ \Delta f_3 \\ \Delta P_{12} \\ \Delta P_{13} \end{bmatrix}. \tag{3.3}$$

Therefore, its derivative vector is:

$$\dot{x} = \begin{bmatrix} s\Delta f_1 \\ s\Delta f_2 \\ s\Delta f_3 \\ s\Delta P_{12} \\ s\Delta P_{13} \end{bmatrix}. \tag{3.4}$$

In this problem, the control variables are the variables related with the reference power, P_{ref}, which defines the amount of power that each area should output. This variables allow us to impose a certain operation on the power plant, being the variables that can be defined externally and are independent of the system state and functioning. However, in order to maintain the system stability the reference powers tend to be defined automatically and in a way to counter act the perturbations verified in the system.

The control vector, u, is constituted by the reference powers relative to all the different areas:

$$u = \begin{bmatrix} \Delta P_{ref1} \\ \Delta P_{ref2} \\ \Delta P_{ref3} \end{bmatrix}. \tag{3.5}$$

The perturbation vector. p, contains the variables that represent perturbations that affect the system state. These variables' value can vary, and, for this problem application consist on the power load variations. The load change is considered a perturbation because its value cannot be controlled, it is a product of the consumers free behaviour so its value is not certainly known. Naturally there are prediction models which can determine within a certain level of uncertainty the load value for a given area, for a given time period. However deviations can be verified especially in contingency conditions.

The perturbation vector is then defined as follows,

$$p = \begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \\ \Delta P_{D3} \end{bmatrix}. \tag{3.6}$$

In order to obtain the state model representation for the system under study, one must find the equations that describe the model before. By analysing the block diagram that represents the three-area system it is possible to obtain the equations relating the variables in play. More specifically, each node or summation block will allow us to obtain an equation relating its inputs and outputs.

First, by analysing the two sum blocks on right-hand side of the figure 2.12, one can write the equations that relate the power transmitted between areas and the frequency difference between them:

$$sP_{12} = T_{12}(\Delta f_1 - \Delta f_2), \tag{3.7}$$

$$sP_{13} = T_{13}(\Delta f_1 - \Delta f_3). \tag{3.8}$$

Where T_{12} and T_{13} are compact ways of writing $\frac{2\pi}{X_{12}}$ and $\frac{2\pi}{X_{13}}$, respectively.

Next, from the sum block in area 1, on the left hand side, the following equation can be written:

$$(2H_1 s + D)\Delta f_1 = -\frac{1}{R\sigma}\Delta f_1 + \frac{1}{\sigma}\Delta P_{ref1} - \Delta P_{D1} - \Delta P_{12} - \Delta P_{13}. \tag{3.9}$$

By reorganising 3.9 thought algebraic manipulation one can obtain:

$$s\Delta f_1 = -\frac{1}{2H_1}(\frac{1}{R\sigma} + D)\Delta f_1 + \frac{\Delta P_{ref1}}{2H_1} - \frac{\Delta P_{D1}}{2H_1} - \frac{\Delta P_{12}}{2H_1} - \frac{\Delta P_{13}}{2H_1} \tag{3.10}$$

From the sum block in area 2, on the left hand side, the following equation can be written:

$$2H_2 s\Delta f_2 = \Delta P_{ref2} - \Delta P_{D2} + (H_3 K_{G2} + \frac{sK_{dmp2}}{s+1})\Delta f_2 + \Delta P_{12} \tag{3.11}$$

By algebraic manipulation it is obtained:

$$\begin{aligned} s\Delta f_2 = \frac{s+1}{2H_2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}\Delta P_{ref2} - \frac{s+1}{2H_2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}\Delta P_{D2} - \\ -\frac{K_{G2}+2}{2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}\Delta f_2 - \frac{1}{2H_2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}s^2\Delta f_2 + \\ +\frac{1}{2H_2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}\Delta P_{12} + \frac{T}{2H_2(\frac{K_{G2}}{2} + 1 - K_{dmp2})}(\Delta f_1 - \Delta f_2) \end{aligned} \tag{3.12}$$

From the sum block in area 3, on the left hand side, the following equation can be written:

$$2H_3 s\Delta f_3 = \Delta P_{ref3} - \Delta P_{D3} + (H_3 K_{G3} + \frac{sK_{dmp3}}{s+1})\Delta f_3 + \Delta P_{13} \tag{3.13}$$

By algebraic manipulation it is obtained:

$$
\begin{aligned}
s\Delta f_3 = & \frac{s+1}{2H_3(\frac{K_{G3}}{2}+1-K_{dmp3})}\Delta P_{ref3} - \frac{s+1}{2H_3(\frac{K_{G3}}{2}+1-K_{dmp3})}\Delta P_{D3} - \\
& -\frac{K_{G3}+2}{2(\frac{K_{G3}}{2}+1-K_{dmp3})}\Delta f_3 - \frac{1}{2H_3(\frac{K_{G3}}{2}+1-K_{dmp3})}s^2\Delta f_3 + \\
& + \frac{1}{2H_3(\frac{K_{G3}}{2}+1-K_{dmp3})}\Delta P_{13} + \frac{T}{2H_3(\frac{K_{G3}}{2}+1-K_{dmp3})}(\Delta f_1 - \Delta f_3)
\end{aligned}
\tag{3.14}
$$

Then, it is necessary to define the matrices A, B and P. This is done by writing 3.10, 3.12, 3.14, 3.7 and 3.8 in matrix form and comparing them with the defined vectors x, u and p. Therefore, the matrix A is given by:

$$
A = \begin{bmatrix}
\frac{-1}{2H_1\sigma R} & 0 & 0 & \frac{-1}{2H_1} & \frac{-1}{2H_1} \\
\frac{T_{12}}{2H_2+K_{dmp2}+H_2K_{G2}} & -\frac{T_{12}+H_2K_{G2}}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 \\
\frac{T_{13}}{2H_3+K_{dmp3}+H_3K_{G3}} & 0 & -\frac{T_{13}+H_2K_{G3}}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & \frac{1}{2H_3+K_{dmp3}+H_3K_{G3}} \\
T_{12} & -T_{12} & 0 & 0 & 0 \\
T_{13} & 0 & -T_{13} & 0 & 0
\end{bmatrix}
\tag{3.15}
$$

The matrix B can be written as:

$$
B = \begin{bmatrix}
\frac{1}{\sigma 2H_1} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\tag{3.16}
$$

The matrix Γ can be written as:

$$
\Gamma = \begin{bmatrix}
\frac{1}{\sigma 2H_1} & 0 & 0 & 0 & 0 \\
0 & \frac{1}{2H_2+K_{dmp2}+H_2K_{G2}} & 0 & 0 & 0 \\
0 & 0 & \frac{1}{2H_3+K_{dmp3}+H_2K_{G3}} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\tag{3.17}
$$

Note that for the matrices B and Γ extra lines and columns filled with zeros were added in order to match the needed matrix dimensions. The vectors u and p also have to add lines filled with zeros in order to match the desired dimensions.

It is important to notice that up until this point all the models and equations are in its s-domain form. So, it is necessary to apply a method to obtain the results in the time domain. Once the results are in the time domain form it is possible to obtain the system's frequency response.

In order to obtain the response from the system in the time domain, a change of variables should be applied to the state model matrices. The change of variables is used because it is desirable to operate with a diagonal matrix, so, the following change of variables is applied,

$$x(t) = Mq(t), \tag{3.18}$$

where M is the modal matrix. It can also be written as,

$$q(t) = M^{-1}x(t). \tag{3.19}$$

Applying the variable change 3.18 to 3.1 the following is obtained,

$$M\dot{q} = AMq(t) + Bu(t) + \Gamma p(t). \tag{3.20}$$

Solving 3.20 in order to $\dot{q}$, we obtain,

$$\dot{q} = M^{-1}AMq(t) + M^{-1}Bu(t) + M^{-1}\Gamma p(t). \tag{3.21}$$

In a more compact way,

$$\dot{q} = Jq(t) + B^{norm}u(t) + \Gamma^{norm}p(t). \tag{3.22}$$

The matrix M is the modal matrix, i.e., the matrix containing the eigenvectors of the A. The J matrix is the diagonal matrix with the eigenvalues of the matrix A in its diagonal.

In order to simulate a perturbation to the system, the desired variation should be inserted in either vector u or p, depending on the desired simulation. For example, if there is a 50 % decrease in P_{ref2} the vector u is given by,

$$u = \begin{bmatrix} \Delta P_{ref1} \\ \Delta P_{ref2} \\ \Delta P_{ref3} \end{bmatrix} = \begin{bmatrix} 0 \\ 0.5 \\ 0 \end{bmatrix}, \tag{3.23}$$

and, as there are no other perturbations in the system, the vector p is

$$p = \begin{bmatrix} \Delta P_{D1} \\ \Delta P_{D2} \\ \Delta P_{D3} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \tag{3.24}$$

So,

$$\dot{q} = Jq(t) + B^{norm}u(t). \tag{3.25}$$

The solution to this differential equation is

$$q(t) = J^{-1}(e^{Jt} - I)\Gamma^{norm}p(t). \tag{3.26}$$

In the end, one must return to the initial variable, using 3.19. This methodology will allow us to obtain the time response of the system when introducing any perturbation. It can be useful not only to analyse the importance and the impact of each variable but also to dimension certain values for the PV emulations, namely the emulated inertia and the damping factor.

3.3 Simulation

In this section, more details regarding the computer simulation will be presented. Namely, how the computer program operates in order to describe the desired model and the chosen parameters' values. Also, the reasoning behind the choices for parameters' values will be discussed.

The computer program was developed in MATLAB and it aims to simulate the three-area system presented in 2.12. The model was approached with the state model methodology, that was described in the previous section. After that, the variable change was performed in order to present the results in the time domain.

The main variables whose behaviour was monitored and represented in graphs were the frequencies in all the three areas as well as the power transferred between them. The system perturbations will depend on each particular case that is desired to be modelled and will be explained in detail in the next chapter.

The values for each simulated parameter are presented in table 3.1. However, it is important to consider that for some specific simulations the value may be different from the presented. All the parameter deviations from the values present in 3.1 are presented and explained in each case study.

Table 3.1: Parameter values used for simulation [2], [3]

H_1	10 s
H_2	3 s
H_3	3 s
D	1
K_{G2}	55
K_{G3}	55
K_{dmp2}	1
K_{dmp3}	1
σ	0.1
R	0.04
X_{12}	0.1
X_{13}	0.1

The reasoning behind the established inertia values for each power plant in the different areas is to represent the real system composed by three power plants, the thermal, the PV power plant and the wind park, as accurately as possible. The inertia constant, H, is highly dependent on the dimension of the power plant and its nominal capacity: the higher the capacity the higher the inertia constant. Knowing that the power plant installed in area 1 is the thermal power plant and that it has the double of the capacity, 200 MW, of the other two, it makes sense that its inertia value is highest. Also, it is important to consider that this is the only power plant in the simulated system that has physical inertia stored as kinetic energy. The other two inertia constants, corresponding to area 2 and 3, are inherent to the operation of the voltage synchronous generator, VSG. Therefore, as both areas have the same capacity, the VSG operation in each power plant would be equal, having the same value of inertia value.

Considering the stated differences between the power plants in dimension and operation nature, I considered the inertia constant values of 10 seconds for the thermal power plant, present in area 1, and the value of 3 seconds for the power plants based on renewable resources, present in area 2 and 3. Also, these inertia constant values are base on the typical values, indicated in [2], for power plants with the same capacity.

The transmission lines' reactance value, X_{12} and X_{13}, as well as the value of σ were based on typical values used in frequency control modelling, suggested in [2]. The values of the droop coefficients, K_{G2}, K_{G3}, and damping coefficients, K_{dmp2}, K_{dmp3} were tuned by trial and error until the desired behaviour was achieved, as was suggested by the model author in [3].

With the system modelled and all its parameters defined it is possible to simulate different perturbations and obtain the frequency response and the power transmitted between areas. The simulations and their details will be presented and discussed in the next chapter.

4

Simulation Results and Analysis

Contents

In this chapter, the simulation results from five experiments are presented, explained and analysed. In each experiment, the real-world phenomenon that is desired to be simulated is presented and transposed, through parameter manipulation, to the three-area model, represented in 2.12. After, the simulation results will be presented focusing on the frequency deviations and the power transmitted between areas.

Once the results are presented they are carefully analysed to draw meaningful conclusions from the simulated experiments. Therefore, contributing to a better understanding of the virtual synchronous generator relevance in a system with a lot of energy production dependent on renewable energy sources.

4.1 Result Presentation's Assumptions

Before observing the results it is extremely important to know and fully understand the system's initial conditions and how the simulation results will be presented and analysed. This information is vital to be able to analyse what is happening in the system and translate it to actual conclusions.

First of all, it is important to know the system's initial conditions or the system initial state. For this work, it is considered that before the perturbation occurs the system has all the three power-plants operating, and all of them are able to feed the respective load on the area. Therefore, none of the three areas is depending on the others in order to fulfil the power demand. Naturally, this condition translates to a null value of power transmitted between areas and, as the power produced is the same as the power demand in each area, all the area's frequency is at the rated value. So, in short, the simulations will consider variations around an operating steady-state point.

It is also considered that the perturbation occurs at $t = 0s$, so any variation on any variable that is verified after this instant can be classified as a result or a consequence of the perturbation.

Regarding the units used to describe the different variables, all the values are referred in per unit, pu, unless stated otherwise. For example, if there is a drop of 0.2 in the frequency it means a 20% drop which corresponds to a drop of 10 Hz.

It is also important to make a clear distinction between the frequency value, f, and the frequency variation, Δf. So, a frequency drop of 0.2 corresponds to a drop of 10 Hz, which means a frequency value of 40 Hz.

The signal of the value from the analysed variable also has a very well defined meaning. In the frequency variation variables, Δf_1, Δf_2, Δf_3, a negative value denotes a drop in the frequency. For example, if $\Delta f_1 = -0.1$ it means that the frequency is 10% below its rated value, and does not mean a negative frequency in any way.

For the transmitted power variables, ΔP_{12}, ΔP_{13}, the negative signal has a completely different physical meaning. For these variables the signal simply indicated the power flow direction. For example, if ΔP_{12} is positive it means that the power is flowing from area 1 to area 2, on the other hand, if ΔP_{12} is negative it means that the power is flowing from area 2 to area 1.

Having defined not only the system initial conditions but also the result presentation notation and assumptions we are now ready to simulate different perturbations under distinct conditions to study the system and evaluate the importance of the virtual synchronous generator.

4.2 Case Study 1

The purpose of the first experiment is to give us a general idea of how the system will respond to the perturbations. Namely, analyse the frequency deviation response in all the areas, which are represented by the variables Δf_1, Δf_2, Δf_3. And also analyse how the perturbations will influence the power transmitted between the two areas, ΔP_{12}, ΔP_{13}.

The fist simulation is also extremely important given that it allows us to compare the obtained results with those from other experiments, setting a base case. Knowing the base case makes it easier to identify and analyse the effect of the changes between experiments, being different parameter values, or different perturbations.

For this experiment, it is considered that the power plants based on renewable energy sources are contributing with an inertial response, hence having a VSG installed. Namely, the inertia constant values for each power plant are as presented in 4.1.

Table 4.1: Inertial Constants for Simulation 1

H_1	10 s
H_2	3 s
H_3	3 s

In this situation, the program is intended to simulate a sudden increase in power load demand located in area 3. More specifically, an increase of 30% of the power plant's nominal power capacity, which corresponds to 30 MW. The frequency variation and transmitted power between areas variation are as represented in 4.1 and 4.2, respectively.

By analysing 4.1 one can immediately notice that the frequency variations in all three areas are distinct. The frequency in area 3 drops the lowest, decreasing about 1 % of its nominal value. This behaviour is expected given that the perturbation occurred in area 3, so it will suffer the most with the perturbation. Then, one can observe that the frequency in area 1 is more affected than the frequency in area 2, which could be unexpected knowing that the power plant in area 1 has a much higher inertia constant. However, the frequency in area 1 drops earlier because the area 1 is physically closer to area 3, where the perturbation is present than area 2. Finally, the frequency in all areas converge to the same

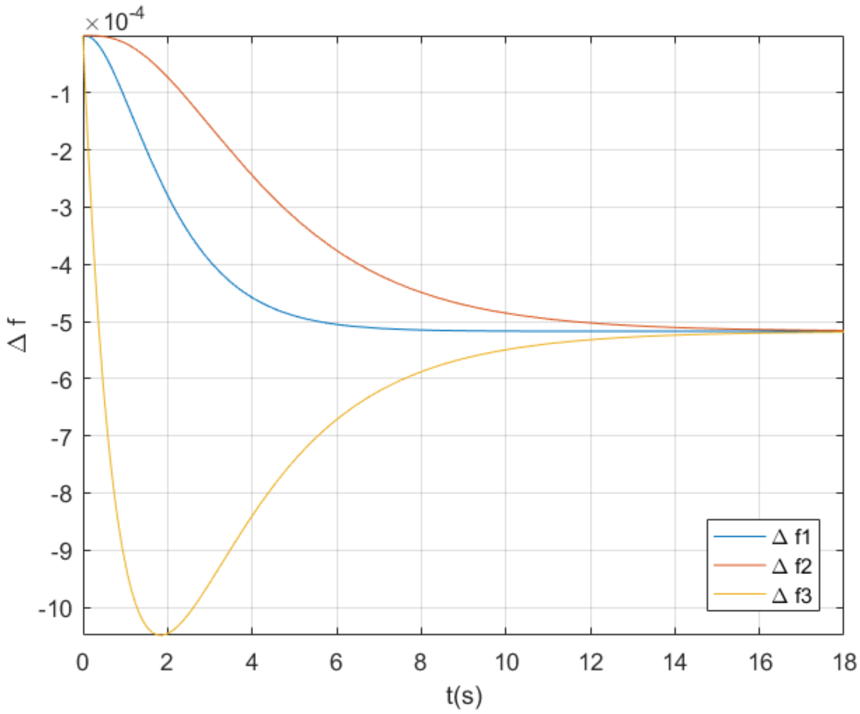

Figure 4.1: Frequency variation response to a 30% increase in power demand in area 3.

value because even with the areas compensating each other's frequency, the increase in load demand is still present, so the power demanded is higher than the power generated, leading to a frequency lower than its nominal value.

Regarding the transmitted power deviations it is possible to observe in 4.2 that the two curves look completely distinct. The value of ΔP_{13} is positive because the power is flowing from area 1 to area 3, while the value of ΔP_{12} is negative because the power is flowing from area 2 to area 1. Also one can verify that the absolute value of ΔP_{13} is higher than ΔP_{12} which is also expected, especially because not only area 1 has more capacity to compensate the lack of power in area 3 but also all the power compensation from area 2 has to go through line 1-3 to reach the area 3. It is also important to notice that the final values for the frequency transmitted in both lines are not null. Naturally, as the perturbation is still present, the areas 1 and 2 still have to provide power compensation to area 3, in order to hold its frequency.

These simulation results highlight the events that were triggered by the perturbation in area 3. These events consisted in: a drop in frequency in all the three areas, and a change in power flowing through the transmission lines. Naturally, the frequency drop was more severe where the perturbation occurred, in area 3, and after some time the frequency tends to the same value in all areas. So, one can say that there is a clear frequency compensation from the areas 1 and 2 to the area 3 minimising the perturbation's effects. This compensation can be observed in the power flowing from both area 1 and 2 to the area 3,

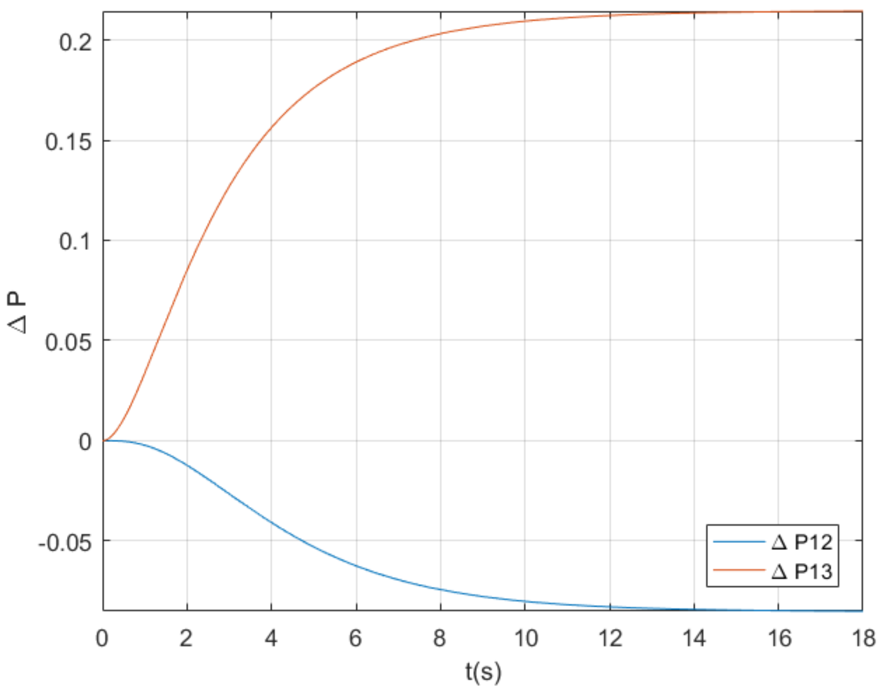

Figure 4.2: Transmitted power variation response to a 30% increase in power demand in area 3.

where the load demand increase occurred.

The obtained results presented in the figures 4.1 and 4.2 show the expected behaviour from three interconnected areas when facing a load increase, as described in [2]. The results also highlight that the introduction of virtual synchronous generators in the power plants based on renewable energy sources allowed them to contribute to frequency compensation, as suggested by the literature sources such as [5].

4.3 Case Study 2

In this experiment, the objective is to observe how the system would respond if the power plant area 3, the PV power plant, would not contribute with an inertial response. So, the PV power-plant is lacking the virtual synchronous generator functioning in this simulation, enhancing how important the VSG contribution is to the frequency variations. Regarding the perturbation to the system, it is equal to the perturbation from the first experiment: a load increase of 30% of its nominal value.

In order to emulate the lack of inertia provided by the virtual synchronous generator, the inertia constant parameter that corresponds to power-plant 3 will be lowered to make it much less significant and neglectable compared with the inertial contribution from the other areas. So, the inertia values for all the power-plants are as presented in 4.2.

Table 4.2: Inertial Constants for Simulation 2

H_1	10 s
H_2	3 s
H_3	0.001 s

With the described changes to the system the obtained results of frequency and power variation are presented in 4.3 and 4.4, respectively.

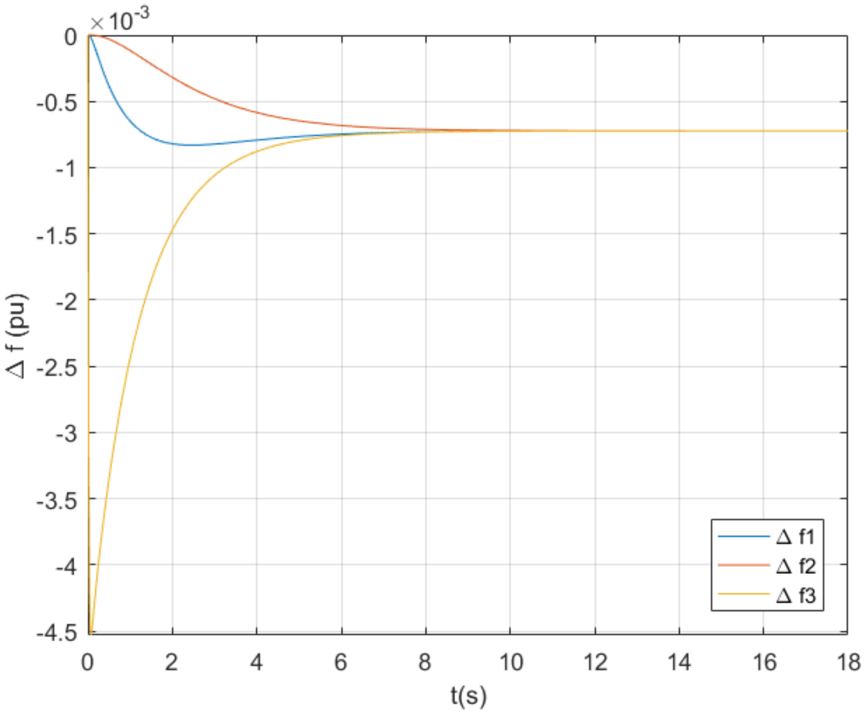

Figure 4.3: Frequency variation response to a 30% increase in power demand in area 3, without inertial contribution from area 3.

In 4.3 it is possible to observe that the frequency in area 3 drops 4.5 %, and the frequencies of all areas converge to the value of less than 0.75% than its nominal value. This huge frequency drop occurs due to the lack of inertial response from the power-plant in area 3, which had a sudden load increase. This level of frequency drop could seriously compromise the correct functioning of the system. Not only a low frequency value is reached but it also takes over 2 seconds for the frequency value in area 3 to recover to less than 1% frequency deviation from the nominal value.

Regarding the power transmitted between lines, represented in 4.4, the phenomena are quite similar to the experiment 1: the areas 1 and 2 have to compensate the frequency in area 3 and help it return to a value close to the nominal value. The main difference between the two initial experiments regarding power transmitted is that in the second experiment, the frequency in area 3 is completely dependent on

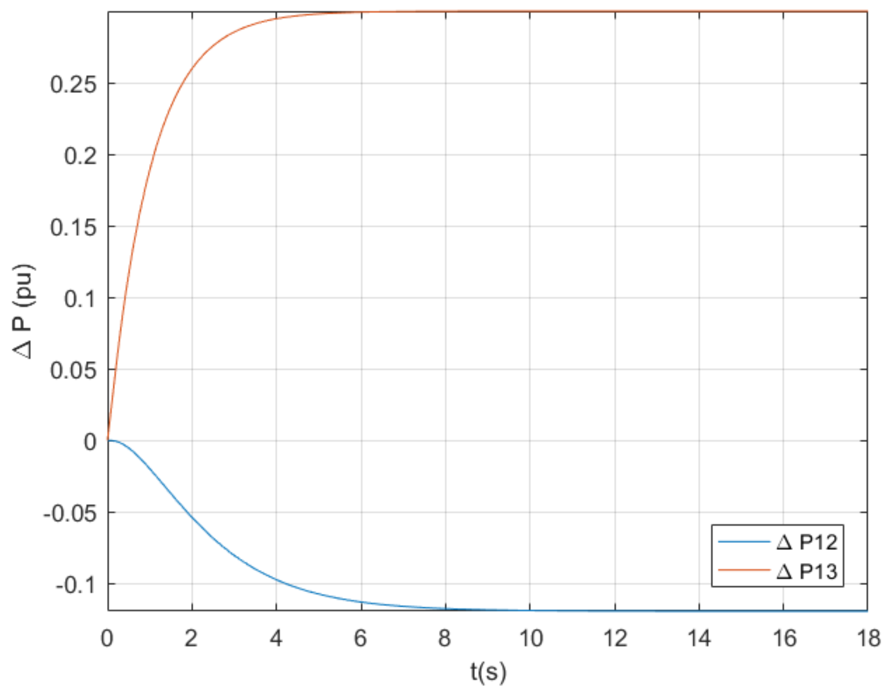

Figure 4.4: Transmitted power variation response to a 30% increase in power demand in area 3, without inertial contribution from area 3.

the other areas. Namely, it is possible to observe in 4.4 that the power transmitted from area 1 to area 3, which corresponds to both the contributions from area 1 and 2, converges to 0.3 pu, which corresponds to 30 % of the rated power. So, all the extra demand imposed by the system perturbation has to be supplied by other areas, while in the first case, represented in 4.2, the power transmitted from area 1 to area 3 is lower than the total needed to accommodate the perturbation. Hence, in the first case there is a clear capacity from area 3 to self-compensate its perturbation, while when no virtual inertia was present, the area was fully dependent on the other areas.

4.4 Case Study 3

With the previous case studies, it was possible to observe that the interconnection between the areas was extremely relevant to compensate the frequency drop originated by the perturbations occurred in a given area. It would be interesting to evaluate how important the interconnection that ties the different areas, allowing power flow between areas, actually is. In order to study that, this simulation will test the system while the area 3 is not connected to other areas, as if area 3 is in an island condition while having the virtual synchronous generator contributing with an inertial response from the power-plant in area 3.

In this system, the lack of connections to area 3 will be simulated by attributing a high value to the

1-3 line impedance. If the line impedance is much higher than it was, for example, an impedance in the order of millions of pu, the system will behave as if that connection was non-existent, and would represent an open-circuit.

Regarding the perturbation imposed, it will be the same that was used in the earlier experiments: a sudden increase of 30 % of load demand in area 3. The inertial constants, which are presented in 4.3, will be the same as in the first case study.

Table 4.3: Inertial Constants for Simulation 3

H_1	10 s
H_2	3 s
H_3	3 s

Once the parameter changes, that were described before, were applied to the simulation, the results obtained are represented in 4.5 and 4.6.

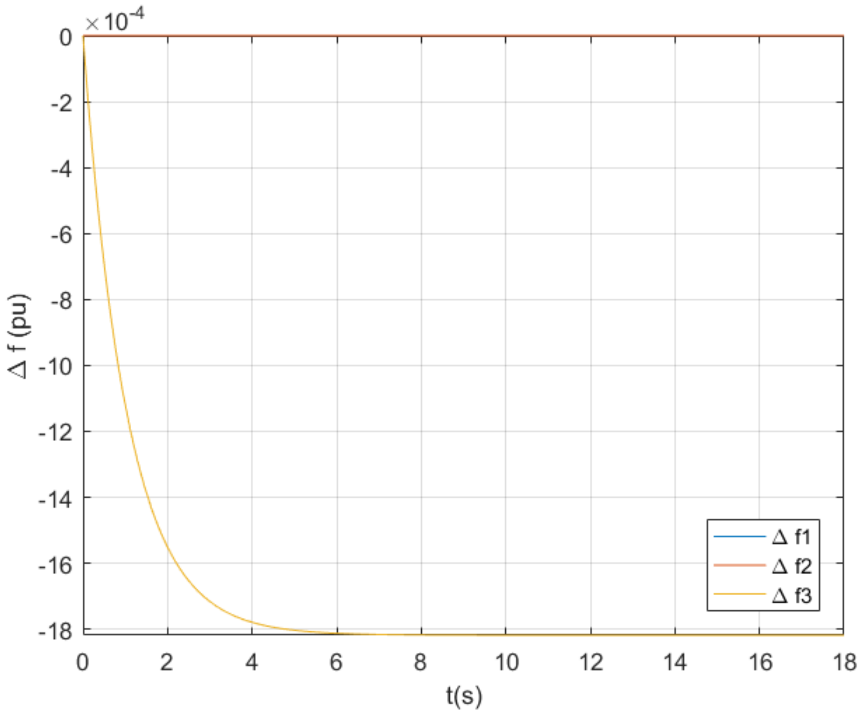

Figure 4.5: Frequency variation response to a 30% increase in power demand in area 3, without interconnection to any other area.

In this simulation, the area 3 has to counteract the perturbation on its own. Only the PV power-plant in area 3 will contribute to frequency stability, which is equipped with a virtual synchronous generator to output an inertial response, to hold the frequency value. One can observe in 4.5 that the frequency in area 3 drops 1.8 % of its rated value and it stays at that value. As expected, the frequency in areas 1

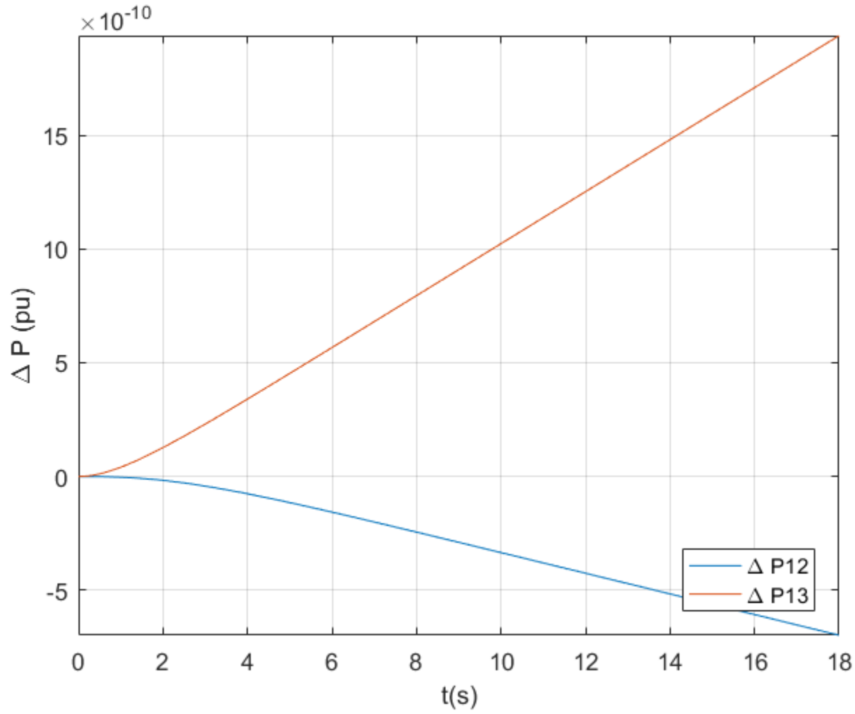

Figure 4.6: Transmitted power variation response to a 30% increase in power demand in area 3, without interconnection to any other area.

and 2 stays the same: at the rated value, so the perturbation in area 3 does not affect the frequency in the other areas. This result is significantly different from the one verified in the first case study, in 4.1, where the areas 1 and 2 affected their frequencies to supply extra power to area 3, to keep its frequency higher.

If the main objective is to keep all the areas functioning, the case study 1 offers the best final state for the whole system. However, if the priority is to keep the area 1 or 2 in perfect conditions, namely at rated frequency value, cutting off the connection between these areas and the area which is suffering a perturbation can be advantageous. Naturally, the ideal way of operating the system will always depend on the system's main goal.

The power transmitted through the lines, represented in 4.6, is extremely low when compared to the rated power, so it is can be neglected given that it has no physical meaning. As area 3 is disconnected from the other areas there is no power flowing, which was expected given the initial simulation conditions.

4.5 Case Study 4

For the fourth experiment, it would be interesting to understand how important the virtual synchronous generator is in the frequency response while area 3 has no connection to any other area. In order to understand the VSG influence, in this experiment, the virtual synchronous generator function will be removed, and the new results will be analysed and interpreted.

Naturally, to remove the voltage synchronous generator from the PV power-plat installed in area 3, the parameter to be affected is the inertia constant of than area, H_3, which will have a value much lower that the usual values, making that power-plant have a neglectable impact in the inertial response to hold the frequency. The inertia constant values for this experiment are detailed in 4.4.

Table 4.4: Inertial Constants for Simulation 4

H_1	10 s
H_2	3 s
H_3	0.001 s

Once the parameter changes were applied to the simulation, the results represented in 4.7 and 4.8 were obtained.

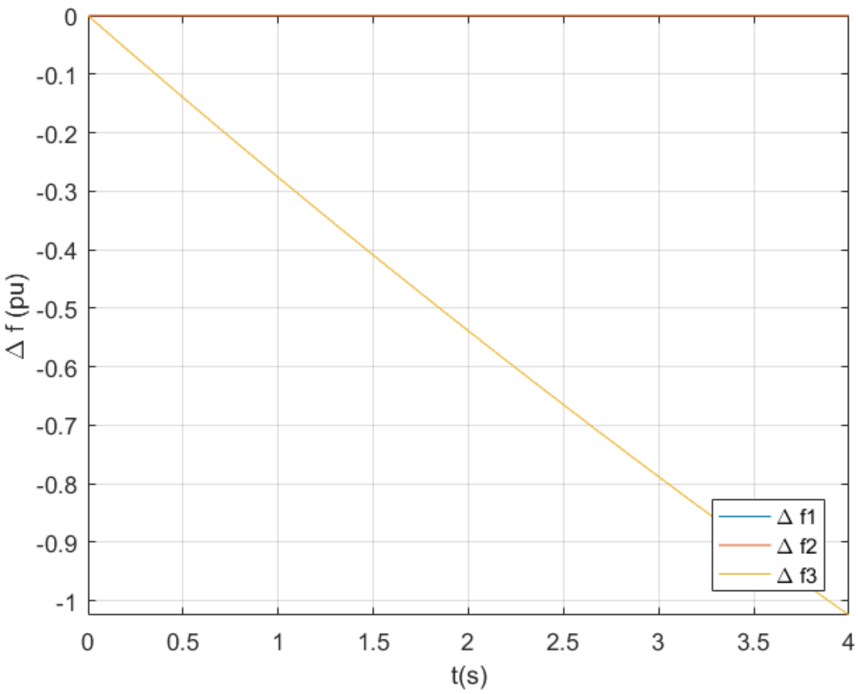

Figure 4.7: Frequency variation response to a 30% increase in power demand in area 3, without interconnection to other areas and without inertial contribution from area 3.

In 4.7 one can observe the most severe response from the system when subjected to the load increase. Without the inertial contribution from the virtual synchronous generator, and without the support from any other area the frequency in area 3 collapses. In 2 second the frequency drops to 50% of its rated value, making evident that the area 3 alone can not compensate the perturbation. The frequency

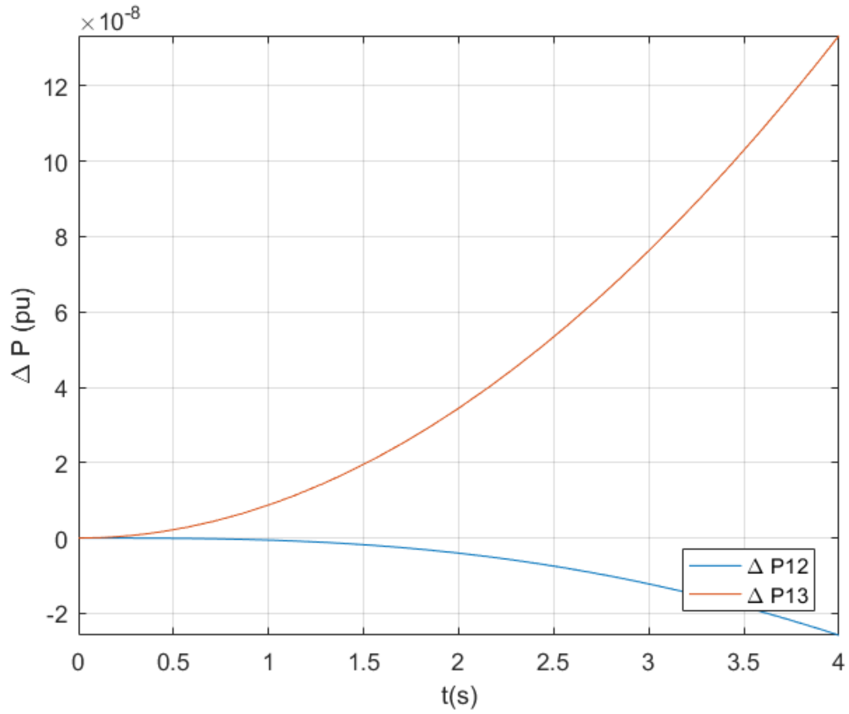

Figure 4.8: Transmitted power variation response to a 30% increase in power demand in area 3, without interconnection to other areas and without inertial contribution from area 3.

dropped and there were not enough resources to hold it near the rated value, causing a power system collapse in area 3, therefore affecting all the existing load in the area.

The areas 1 and 2 stay at the normal operation point, at rated frequency, thanks to the loss of connection with the area 3. This makes it impossible for the power to flow from areas 1 and 2 in order to compensate for the perturbation that occurred in area 3. However, the power values, present in 4.8, are not exactly null as one may expect. This can be attributed to the fact that the simulated line impedance that connects the areas 3 and 1 is not infinite, allowing a small power amount to flow. This power flow is present only in the simulation, and it is not present in the physical situation that is desired to be modelled. So, given the magnitude of the power values obtained, considering that the power flowing is one million times lower than the rated power, one can conclude that these values are neglectable and have no physical meaning.

This simulation highlights the concerns expressed by some authors, [8] and [9], that when having an area fully supplied by power plants based on renewable energy sources, a perturbation can cause the frequency to collapse. Naturally, as the area 3 is disconnected from any other area, it represents a 100% penetration level of RES for that area. Therefore, this situation should be avoided in real systems by whether installing virtual inertia in RES-based power plants or operate the network in a way that areas with low inertia are never disconnected from the grid, so they can be compensated.

4.6 Case Study 5

For the last simulation, it would be relevant to introduce a different perturbation on the system, especially given that all the previous case studies are responses to the same perturbation. Also, the sudden increase in load demand is a perturbation that could occur in any power system, so, it would be interesting to simulate an occurrence inherent to a system with high renewable penetration.

When a power system is mostly dependent on power-plants that generate power from renewable sources it is extremely important to consider the power resource availability. For example, a PV power-plant is highly dependent on weather conditions, which can rapidly change, affecting the power output capacity. Any weather event that affects the irradiance, the quantity used to describe the solar the power of the incident radiation, expressed in W/m^2, also affects the power-plant output can then be considered as an external perturbation.

In this section, a sudden irradiance drop, caused by the presence of clouds, will be simulated. However, the modelled system does not have a variable that directly describes the irradiance on the PV panels, so, to simulate this perturbation, one has to operate on the modelled variables.

The variable ΔP_{ref3}, as stated in previous chapters, describes the amount of power that the power-plant 3, namely the PV, is desired to be outputting. Naturally, this value is controllable as long as it is lower than the maximum power output. So, it could be used to simulate a sudden drop in power out, which is caused by the undesired weather conditions.

Therefore, to simulate a 30% drop in power production in the power-plant installed in area 3, a 30% drop will be introduced in the reference power variable, ΔP_{ref3}.

Similarly to the other case study experiments, the frequency response and the power transmitted through the lines that connect the different areas are presented in 4.9 and 4.10, respectively. The inertia constants values are the same as in the case study 1: all the units are contributing to the inertial response of the system. It was also considered that the lines connecting the areas are in normal operation.

By analysing 4.9 one can immediately notice that the frequency variations in all three areas are distinct. The frequency in area 3 drops the lowest, decreasing about 1 % of its nominal value. This behaviour is expected given that the perturbation occurred in area 3, so it will suffer the most with the perturbation. Then, one can observe that the frequency in area 1 is more affected than the frequency in area 2, which could be unexpected knowing that the power plant in area 1 has a much higher inertia constant. However, the frequency in area 1 drops earlier because the area 1 is physically closer to area 3, where the perturbation is present than area 2. Finally, the frequency in all areas converge to the same value because even with the areas compensating each other's frequency, the increase in load demand is still present, so the power demanded is higher than the power generated, leading to a frequency lower than its nominal value.

Regarding the transmitted power deviations it is possible to observe in 4.10 that the two curves look

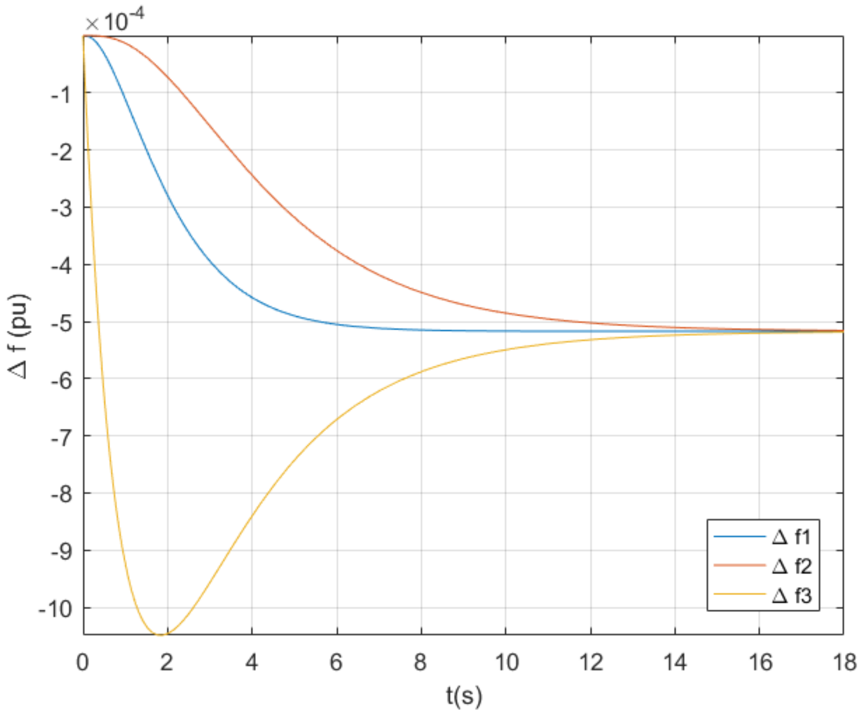

Figure 4.9: Frequency variation response to a 30% decrease in power production in area 3.

completely distinct. The value of ΔP_{13} is positive because the power is flowing from area 1 to area 3, while the value of ΔP_{12} is negative because the power is flowing from area 2 to area 1. Also one can verify that the absolute value of ΔP_{13} is higher than ΔP_{12} which is also expected, especially because not only area 1 has more capacity to compensate the lack of power in area 3 but also all the power compensation from area 2 has to go through line 1-3 to reach the area 3. It is also important to notice that the final values for the frequency transmitted in both lines are not null. Naturally, as the perturbation is still present, the areas 1 and 2 still have to provide power compensation to area 3, in order to hold its frequency.

After analysing 4.9 and 4.10 one can verify that the simulation results from this case study are exactly equal to the results obtained in the first case study. This suggests that both perturbations: a 30% increase in load demand and a 30% decrease in power production have the same effect on the system frequency, and therefore the same effect on the power transmitted between lines. The similarity between both results can be explained by analysing the system's block diagram, in 2.12, where both variables ΔP_{ref3} and ΔP_{D3} are present on the same diagram node with opposite signals. So, an increase in power demand in area 3, ΔP_{D3}, is equivalent to a decrease in power production, as long as they both changes have the same magnitude, and vice versa.

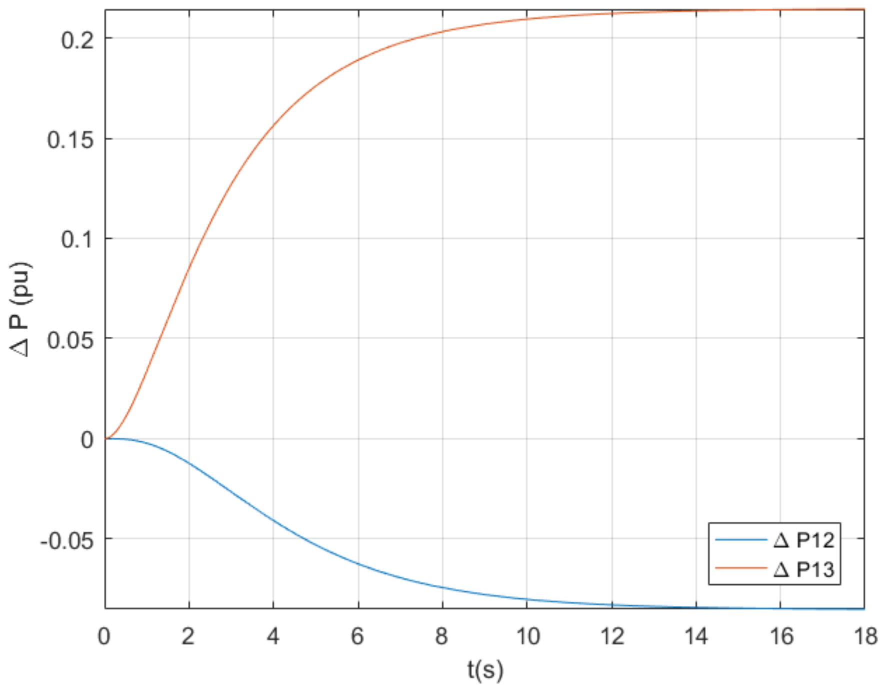

Figure 4.10: Transmitted power variation response to a 30% decrease in power production in area 3.

5

Final Considerations

Contents

In this chapter, the final considerations regarding the conclusions from the work developed throughout this thesis will be presented. The four main points that lead us to the conclusions are the model produced and methods applied, the impact of RES-based power plants on the grid, the effects introduced by the virtual inertia and its impact on the future of power systems.

5.1 Model and Methods

The three-area model, obtained from the existing literature, is the foundation of all the simulation results produced and presented in this work. Therefore, it is important o assess its reliability in order to analyse the obtained results. Without a reliable model, it is not possible to obtain reliable results that lead to relevant conclusions.

The first experiment presented in the previous chapter, 4, simulates a load increase which is a classical problem, having been studied for decades, [2]. So, the result from such simulation is well-known and the model produced in this work was able to reproduce the expected result. This allied to the fact that results from the other simulations were also what one would expect, allows us to accept the model's validity for the developed experiments.

Despite all the simplifications and approximations made in order to obtain a simpler model, it still produced reliable results which enable the formulation of significant conclusions. This is the first conclusion of this work: the obtained model, in 3, is reliable and the simulation results obtained from it present a good approximation of the real three-area system, for the experiments under study.

5.2 The Impact of RES-based Power Plants

Many authors have suggested that the increasing penetration level of RES-based power plants in the power system could bring frequency response problems or even instability, [9] and [8]. These power plants are not able to present an instantaneous frequency response due to the lack of inertia in its nature.

From the simulation results, presented in 4, it is possible to conclude that, when the RES-based power plants were operating without the virtual inertia compensation, its frequency response was insufficient, being harmful to the system's frequency, 4.3. When testing a perturbation on an area fully dependent on the RES-based power plant, without external compensation nor virtual inertia contribution, the frequency collapsed, 4.7.

The obtained results suggest that it is not possible to fully rely on the production from power plants based on renewable resources without any compensation in order to produce the desired frequency response. Therefore, to achieve a high penetration level of these power plants it is required an inertial contribution to counteract the frequency perturbations.

5.3 Virtual Inertia

The solution under study throughout this work, to enable the increase of penetration level of RES, is the implementation of virtual inertia in the control layers of the power plants, changing its natural behaviour when facing frequency perturbations.

The developed simulations, in 4, highlight the role inertia and how it contributes to the frequency perturbations. When comparing the simulated results where there is no inertia contribution with the case where the VSG is operating, introducing VI, it is possible to conclude that the virtual inertia is vital for the frequency stability. It holds the frequency value by injecting instantaneously power in the grid.

The implementation of devices that install virtual inertia in the RES-based power plants, such as the VSG, present a viable solution to increase the penetration of green energy sources while keeping the reliability of the power system operation. Therefore, these devices will be essential in order to follow the power system evolution.

5.4 Implications in the Power System's Future

The future of the electric power system is moving towards a high level of penetration of RES-based power plants, as high as possible while reducing the thermal power plants' presence. Therefore, a more ecological and sustainable power system will take the role of the old pollutant system.

The future system must still meet the power quality standards and it must also present a stable behaviour, avoiding blackouts. In the previous section, it was stated that virtual inertia can make possible the system operation while having a high level of RES-base power plants penetration. Despite trying to mimic the operation of thermal power plants, virtual inertia is different in nature and scale resulting in differences between the power system dominated by thermal power plants and the future power system.

The new way to introduce inertia to the system, the virtual inertia, relies on energy storage devices, such as flywheels, which will globally represent a lower value of inertia than the synchronous machines. Therefore, the system will present inertia, enabling an initial inertial response to the frequency perturbations, however, it will be lower than before. This results in a more accentuated drop in frequency, or, as referred to in the literature sources, a higher Rate Of Change Of Frequency (ROCOF).

As long as the system is not only adapted to support a slightly higher drop in the frequency but also able to have just enough inertia to counteract the frequency perturbations, the power system will be able to operate reliably, as it has been for centuries.

5.5 Conclusion

To conclude, the scope and objectives of the thesis were fulfilled. The problem under study was presented and explained, as well as the motivations behind its study. Then, a review of the existing literature provided the basis to create the model of the desired system. Once the model was produced, simulated results were obtained, allowing one to study the role of inertia on the power system as well as the impact that the introduction of virtual inertia in RES-base power plants can have on the power system. Finally, it was possible to conclude that the implementation of devices that provide virtual inertia to the power plants that naturally lack inertia is essential to the power system operation with a high level of penetration of RES-based power plants. The implementation of these new devices will enable the power system evolution to become more ecological while keeping its operational reliability.

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