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for the Degree of Doctor in Engineering

EFFECT OF MARKET-DRIVEN MINIGRIDS ON THE FREQUENCY STABILIZATION PROCESS OF ISOLATED MIDDLE-SIZED POWER GRIDS

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to Juan, Rosa and Antonio for their continuous and never ending support

Erklärung

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ABSTRACT

Latest developments on technologies like distributed generation, renewable energy technologies, wholesale electrical market, mini- and microgrids, distributed intelligence and information and communication technologies are outlining the future of the energy world. The integration of these technologies together in a common concept is the purpose of current research efforts towards the idea of the intelligent power grid.

This new concept is based on the following milestones: The supply is tending to be dispersed in an area and not grouped anymore in large power stations; The control is not anymore based only on the supply but also in an agile control of the demand; The inputs to the system are not only mechanical or electrical parameters but also other kind of parameters such as price-signals; The renewable sources technologies are not only connected to the system but fully integrated.

The work presented in this thesis is framed into this new concept of power grids. Although the future is seen as a totally decentralised configuration, a transition is necessary. This transition needs technologies which are able to adapt all these new concepts into current power systems. This work shows that a minigrid can be used as a supporting element for a standard medium-sized isolated power grid.

In order to demonstrate the above statement, a new energy management system for minigrids – called CMS – is developed. This CMS works by optimizing the minigrid's economical profit by acting as an intelligent load, reacting to price signals. Furthermore, when an overloading of the system is detected (by means of a frequency drop), the minigrid switches its behaviour and starts controlling its loads in order to help the main grid in the frequency stabilization process.

This idea was demonstrated with simulations and in a test plant in the laboratory with satisfactory results, showing the feasibility of this new kind of management system.

ZUSAMMENFASSUNG

Neueste Entwicklungen in Technologien für dezentrale Energieversorgungsstrukturen, erneuerbare Energien, Großhandelsenergiemarkt, Mini- und Mikronetze, verteilte Intelligenz, sowie Informations- und Datenübertragungstechnologien werden die zukünftige Energiewelt maßgeblich bestimmen. Die derzeitigen Forschungsbemühungen zur Vernutzung aller dieser Technologien bilden die Voraussetzungen für ein zukünftiges, intelligentes Stromnetz.

Dieses neue Konzept gründet sich auf die folgenden Säulen: Die Versorgung erfolgt durch dezentrale Erzeugungsanlagen und nicht mehr durch große zentrale Erzeuger; die Steuerung beeinflusst nicht mehr allein die Versorgung sondern ermöglich eine auch aktive Führung des Bedarf; die Eingabeparameter des Systems sind nicht mehr nur mechanische oder elektrische Kenngrößen sondern auch Preissignale; die erneuerbaren Energieträger sind nicht mehr nur angeschlossen, sondern voll ins Energienetz integriert.

Die vorgelegte Arbeit fügt sich in dieses neue Konzept des intelligenten Stromnetz ein. Da das zukünftige Stromnetz dezentral konfiguriert sein wird, ist eine Übergangsphase notwendig. Dieser Übergang benötigt Technologien, die alle diese neue Konzepte in die derzeitigen Stromnetze integrieren können. Diese Arbeit beweist, dass ein Mininetz in einem Netzabschnitt mittlerer Größe als netzschützende Element wirken kann.

Hierfür wurde ein neues Energiemanagementsystem für Mininetze – das CMS (englisch: Cluster Management System) – entwickelt. Diese CMS funktioniert als eine von ökonomischorientierte Betriebsoptimierung und wirkt wie eine intelligente Last auf das System ein, reagierend auf Preissignale. Sobald wird durch eine Frequenzsenkung eine Überlastung des Systems bemerkt, ändert das Mininetz sein Verhalten und regelt seine Belastung, um die Stabilisierung des Hauptnetzes zu unterstützen.

Die Wirksamkeit und die Realisierbarkeit des einwickelten Konzept wurde mit Hilfe von Simulationen und erfolgreichen Laborversuchen bewiesen.

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The first team who participated on this work was the people from the Geography team of the University of Balearic Islands (UIB), while this research started as an analyses of the tourist influence in the energy situation on Balearic Islands. Many thanks to Prof. Dr. Pere Salvà for the first impulse and making me seriously consider the possibility of a PhD. Since the interest and background of the author was related to the engineering world, the direction taken by the thesis started earlier being out of the expertise skills of this team.

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Through Eugeni, the author got in contact with a research team at the University of Applied Sciences in Aachen. This team was leaded by Dr. Klaus Dielmann and they formed the author in the field of Virtual Utility and funded her second year of research. Thanks also to Dr. Dielmann for the opportunity he gave to me and his patient with my German language limited skills.

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CHAPTER 1

INTRODUCTION

Concepts like Distributed Generation (DG), Renewable Energy Sources (RES), wholesale electrical market, mini- and microgrids, Distributed Intelligence (DI) or Information and Communication Technologies (ICT) are outlining the future of the energy world. Several efforts by industry, governments, and researchers are defining new needs and strategies for electricity [1].

First efforts in this direction were done in the development of the different RES and Distributed Energy Resources (DER) technologies. Developments in the field of photovoltaics, wind turbines, thermal collectors begin to make these technologies competitive in front of large power stations. As example, capital costs for photovoltaic panels have decreased from more than $50/W in the early 1980s to about $5/W today; while energy costs have declined from about $0.90/kW h in 1980 to about $0.20/kW h [2]. Although this is still higher than the cost of conventional electricity, commercial markets are flourishing in developed countries for remote telecommunications, remote lighting and signs, remote homes and recreational vehicles, and in developing countries for remote power for village homes, clinics, and other uses. The incorporation of Roof-Integrated PV for generating power on buildings is, for example, another rapidly growing area [3].

The framework which favoured the explosion of these technologies can be resumed in three main concepts: sustainable energy supply, climate change and greenhouse emissions.

Increasing access to energy was an especially high priority in the World Summit on Sustainable Development debate in Johannesburg on August 2002. Today more than 1.6 billion people have no access to electricity out of a total population of 6.2 billion. About 2.4 billion rely only on primitive biomass for cooking and heating. In the absence of radical new policies, 1.4 billion will still have no electricity in 30 years time. This is the main result of the "energy & poverty" [4] a groundbreaking study by the IEA showing the magnitude and future trends in the endless circle of energy and poverty. The assurance of a sustainable energy supply for all the world population is one of the main points in the design of energy future supply systems as it is defined on the final report of the "Green Paper" of the European Commission [5].

In the context of the climate change, it is to be noted that measurements from various networks, including those of the Wold Meteorological Organisation's (WMO) Global Atmosphere Watch, continue to indicate an increasing accumulation of carbon dioxide (CO_2) in the atmosphere [6]. Indeed, CO_2 has increased by 31% since 1750. The current rate of increase of greenhouse gases, including CO_2, is unprecedented during at least the past 20,000 years. The global average surface temperature has also increased in the 20th century by about 0.6°C. The Third Assessment Report of the WMO/ UNEP (United Nations environmental program): Intergovernmental Panel on Climate Change (IPCC, 2001) indicates "there is new and stronger evidence that most warming observed over the last 50 years is attributable to human activities". The IPCC also projects that global warming is expected to be between 1.4 and 5.8°C by the end of the year 2100, with implications for all countries in the world. Foreseeing this situation, on December 1997 more than 160 nations met in Kyoto, Japan, to negotiate binding limitations on greenhouse gases emissions for the developed nations, pursuant to the objectives of the Framework Convention on Climate Change of 1992. The outcome of the meeting was the Kyoto Protocol, in which the developed nations agreed to limit their greenhouse gas emissions (GHG), relative to the levels emitted in 1990. The rules for entry into force of the Kyoto Protocol require 55 Parties to the Convention to ratify (or approve, accept, or accede to) the Protocol, including Annex I Parties accounting for 55% of that group's carbon dioxide emissions in 1990 [7]. At the moment, only 43.9% of the emissions have been reached. The two major emissaries of GHG have not ratified the Kyoto Protocol text yet, they are USA and Russian Federation. The other are: Switzerland, Australia, Monaco and Liechtenstein.

After the environment which made possible the emerging and evolution of these technologies, the monitoring and control of these RES and DER and the interconnection with the main grid were the next technical barriers to be overcome. Example of efforts in this direction can be found in several research initiatives and demonstration projects, such as the IRED cluster of projects funded by the European Commission [8].

The key technical issues in the interconnection of RES and DER with the main grid were [9]:

– Voltage Regulation
– Grounding
– Synchronisation
– Protections
– Monitoring, Communication and Control
– Islanding
– Voltage Disturbance

– Frequency Disturbance
– Flicker
– Harmonics
– EMI Protection

To find technical solutions for the presented subjects has been matter of discursion of the different project gathered together in the IRED cluster, mentioned above.

The paradigm shift which is underway between just connecting RES and DER to the grid towards fully integrating RES and DER to the energy system is the next challenge to be undertaken [10].

One of the ways of “integrating” RES is associating them with DER in a coordinated entity called minigrid. By virtue of good match between generation and load, mini- and microgrids have low impact in the power grid, despite a potentially significant level of generation by intermittent energy sources [11]. From the point of view of the main grid, mini- and microgrids can be beneficial as they reduce congestion or other threats to system adequacy, if they are deployed as interruptible or controllable loads that can be partially shed as necessary in response to changing grid conditions [12]. However, in the mini- and microgrid operation some issues have to be considered: to ensure a stable operation during faults and various network disturbances; to manage instantaneous active and reactive power balances, power flow and network voltage profiles [13]; and to optimize the economical profit from the electricity exchange with the main grid.

A step forward in the integration of these mini- and microgrids in the main grid is the use of them as intelligent loads, applying Demand Response Methods. It means that the minigrid has the capability of reacting by inputs of the main grid. Two kinds of Demand Response Methods can be defined, indirect and direct. An indirect method would be the Energy Market, it consists in rewarding the electricity consumer for decreasing the electrical consumption in peak periods. A direct method would be the load shedding by e.g. frequency drops, an example of it would be the introduction of monitoring devices able to shut down loads in peak periods.

This thesis can be considered as an effort towards an efficient integration of RES and DER into a liberalized market. This vision is shared by other projects, emphasizing those which target is to define this emerging market’s rules, i.e. CRISP [14]; or developing new technologies and policies to guarantee a stable and reliable operation of the grid, i.e. GridWise [15].

The outcome of this thesis is relevant for: the grid operator, as this concept can be easily adapted to the recently implemented Demand Responsive programs, such as the NYISO[1] Demand Response Programs [16] in the US; the minigrid operator, which could increase its revenue by using its fast reaction to the wholesale market changes capability; the consumer, optimizing its energy consumption with a “smart” load control without sacrificing comfort [17]; the government energy planners, since this high integration of RES and high efficiency technologies would help in reaching the Kyoto Protocol targets [18].

[1] New York Independent System Operator

A possible picture of what the future energy infrastructures could deserve is the concept of the Virtual Utility (VU), in other bibliography referred as Virtual Power Plant. This new concept is referred to a completely decentralized infrastructure where DG and RES facilities are aggregated in groups, called clusters, and the swarm of clusters act together as a big power plant in a demand-driven market. At the early stages of the development of the VU concept, a hierarchical and centralized control topology was proposed [19]. However, with the new emerging ICT applied to DER and RES [20], concepts like Distributed Intelligence made possible the idea of a market-driven control platform. An added value to this tendency is that criteria like insuring market neutrality, implementing short time operational decisions, bringing decision making close to information,... suggest that network customers are likely in the best position to handle many functions previously performed by the network operator [21].

This work could be framed as an EMS suitable for optimizing the work of one of the clusters in a VU type of infrastructure. Therefore, to differentiate from a global oriented EMS, this concept will be referred as Cluster Management System (CMS).

All the concepts introduced are outlining the development of a new conception of the power grid. This new conception is being named *future intelligent power grid* and due its significance for the correct setting of this thesis in this framework, it has been developed as follows.

1.1 Future Intelligent Power Grid

The idea of Future Intelligent Power Grid grew from the necessity of shaping in a common concept all the ideas and technologies described above. The future intelligent power grid concept has been developed in parallel and independently by different environments, such as United States or the European Union. The result in this case is a different but very similar concept, called in Europe SmartGrid and in United States GridWise.

In order to understand the two visions proposed, the contexts in the two worlds are outlined below as relates to the development of the future intelligent power grid concept; this overview should not be considered as a complete description of each situation beyond what pertains to future intelligent power grids.

In Europe, the energy supply situation can be described as a lack of large amounts of natural resources, a forecast of an increase of the Natural Gas consumption and a high potential for RES. That makes the European policy focused on renewable sources and high efficiency DG technologies. While in U.S. the dependency on external fuel is not that critical and the policy is more focused on clean coal technologies

The Energy markets have relatively strong support in both environments, at nation or state levels as much as federal (or European) level. A difference between them is the more controlled way in which Europe is going about the deregulation and privatization process, setting up regulations like the 2003 EU Directive. Meanwhile, in the U.S., the FERC[2] currently lacks clear jurisdiction over reliability issues and NERC[3] has only

[2] Federal Energy Regulatory Commission

voluntary rules which have proven largely insufficient. The Energy Policy Act 2005 (EPAct 2005) may change this situation.

In the case of the U.S., bottlenecks have been identified in the power grid which complicate wholesale markets and create stability problems. In Europe, the main concern is located in the interconnection infrastructures between the countries. After summer 2003, European as well as U.S. electricity system proved to be equally vulnerable to both transmission and generation problems.

Another big concern in the U.S. are security issues, including both blackouts and terrorist attacks. In the case of Europe a major concern is the growth of the electrical infrastructures following very different patterns in the different countries.

Environmental concerns in Europe are driven by its high commitment in matching the environmental targets of the Kyoto Protocol, while in U.S. by the U.S. Environmental Protection Agency recommendations.

Regarding energy policy, in Europe, the high support to the renewables, Demand Side Management (DSM) and Distributed Generation (DG) results in policy supporting the development of these technologies, as well as the necessary reinforcement of transport and distribution capacity to support them and the reinforcement of the interconnection infrastructures between countries. Policy in the U.S. is more focused on supporting clean coal technologies, with renewables, DSM and DG being a secondary focus.

Reliability in the transmission system in the U.S. ensured by a preventive policy: disruption preparation and response. In the future the EPAct 2005 supports the creation of ERO[4] that will enforce reliability rules mandatory for all the stakeholders in the transmission system. In Europe reliability in the transmission system is still being directed at nation level, at European level the policy supports the creation of the European energy market.

The European Research Area aims to the creation of a genuine 'internal market' in research to increase pan-European co-operation and co-ordination of national research activities. In the U.S., the organization of energy research at both the federal level and the state level are strong and well established.

As a result of this situation the two ideas Smartgrid and GridWise were developed. SmartGrid is the name of the European Technology Platform (ETP_SmartGrid) that deals with the "Vision and Strategy for Europe's Electricity Networks of the Future". SmartGrid aims to achieve flexible, accessible, reliable and economic future electricity networks for Europe:

- Flexible, fulfilling the needs of all the customers
- Accessible, granting access to electric assets to all applicants, particularly for RES and high efficiency local generation.
- Reliable, assuring and improving security and quality of supply.

[3] North American Electric Reliability Council
[4] Electric Reliability Organization

- Economic, providing the best value through innovation, efficient energy management and a playing field.

This vision will be achieved for example by transforming the current electricity grids into an interactive (customers/operators) service network, and by removing the technical obstacles to large-scale deployment and effective integration of distributed and renewable energy sources.

The term GridWise denotes the operating principle of a modernized electric infrastructure framework where open but secure system architecture, communication techniques, and associated standards are used throughout the electric grid to provide value and choices to electricity consumers. The GridWise vision can also be described as seeking to modernize the nation's electric system—from customer appliances and equipment to generation—and create a collaborative network filled with information and abundant market-based opportunities. This vision evokes concepts of seamless plug-and-play technologies and a "society" of devices, while recognizing the need to integrate with and evolve with the extensive, existing traditional infrastructure for secure, reliable and affordable energy. In particular, GridWise introduces the notion of a "transactive" system, integrating market-based transactions with control methods, in a complex, distributed, physical system of intelligent devices.

The similarities of these two visions are obvious, even starting from a different situation as justified above, both of them are based on integrating new information and communication technologies, combining them with active support from electricity consumers; and leveraging the optimizing power of markets, to focus on creating an affordable and reliable power grid. Some differences between the two visions stem from the different contexts in the U.S. and Europe.

Europe's vision is clearly influenced by the concern derived from the wide range of natures and degrees of evolution of the power grids across European countries. The consequence of this concern is identified in the need to have a flexible, reliable and accessible power grid, which basically means a power grid that can fulfill the needs of a wide range of customers and economies. This fact and the lack of indigenous resources result in Europe's emphasis on a distributed grid, where large amounts of DG, RES and loads are controlled by an energy market, the grid flows are bidirectional, and the demand response is automatic. These DG units can be directly connected to the main grid but can also be seen as forming clusters such as minigrids.

The vision in the U.S. is marked by the perceived necessity for increasing security and responding to the predicted growth in the demand. The U.S. expects to use information technologies to increase the use of assets and therefore reduce the pressure to increase investment. More so than in Europe, the vision proposed in the U.S. is mainly related to what is still seen as a largely centralized power grid (with unidirectional fluxes based on, for example, coal technologies) but with a high integration of demand response technologies and some penetration of DG used for additional support to the system, all controlled by various markets.

Therefore, the visions in the two worlds differ mainly in conception of the generation. Europe is more focused on creating a highly distributed environment, with a large penetration of RES and DG, while the U.S. envisions large power stations based on clean coal technologies as basis of the system, where the inclusion of DG is perceived primarily as an increment in the security of the system not as the basis. On the demand side, the visions of both worlds coincide, ultimately targeting automatic demand response controlled by real time markets, although the intermediate paths they may pursue to move toward this target are varied.

1.2 Objectives of the Thesis

The primary aim of this Thesis is to improve the understanding of the behaviour of minigrids under the Energy Market rules in Spain. Optimising the economical profit of the minigrid would mean to act as a load of the system drove by indirect Demand Response methods.

When the system is overloaded the market-based Demand Response methods are not enough to assure the stability of the system. Based on this premise, a second aim is defined: to analyse the behaviour of the minigrid when direct support technologies such as controlled load shedding are applied.

In order to achieve these general aims, the following specific objectives are defined:

- First, to choose the minigrid under study and to define the load shedding capacity of it.

- Second, to contribute in the understanding of the Energy Market rules in the case of Spain and how to link them with the minigrids management.

- Third, to analyse the optimisation process for the minigrids management system.

- Fourth, to develop an energy management system, able to optimise the economical benefit of the minigrid under indirect Demand Response methods, switching to direct methods when necessary.

1.3 Structure of the Thesis

This thesis is divided into seven chapters.

A state of the art, frame of this thesis as well as the main objectives and structure are presented in Chapter one.

Chapter two defines the principles of demand response methods and researches the reaction capability of the chosen minigrid. Several important concepts in which this thesis is based are also introduced.

The concept of the Cluster Management System (CMS) is defined in chapter 3. It includes the description of the three different levels in which this management concept is based, including the energy market operation.

Chapter four develops the CMS first level, the responsible of the minigrid's reaction to price inputs from the energy market. Parameters, equations and optimisation algorithms, necessary to develop the CMS first level software are presented.

An overview of the main power system control parameters such as frequency or voltage control is given in Chapter five. Together with it, the use of a minigrid as a real time frequency stabilization element for the main grid is discussed, and the corresponding software (CMS second level) is developed.

Chapter six describes the main issues that the operation of the minigrid should face under an emergency level. This level is activated, for example, when the main grid falls into a blackout. Although this level has been considered out of the scope of this thesis, this chapter presents the different stability issues that should be accounted for at different operating scenarios.

The experimental part of this thesis is described in Chapter seven. It starts with the CMS first level; this software set the initial conditions of the minigrid. After, an imbalance in the power fluxes in the main grid is provoked. This decrease switches the CMS level from first to second. Description of the pilot plant, results of the experiment and conclusions are provided in this chapter.

The last chapter, Chapter eight, presents the main conclusions of this thesis and an outlook of the future work to be done in this field.

CHAPTER 2

DEMAND RESPONSE CAPABILITY

The demand response capability of a minigrid depends on the control of its energy generation and consumption. Depending on the management philosophy used (e.g. based on direct or indirect methods) these parameters can be modified inside a range; Therefore giving a degree of freedom to the operation of the minigrid.

This chapter describes the generation resources in the minigrid and identifies the response capability of the demand.

2.1. The minigrid

The minigrid studied in this research work is called ParcBIT. ParcBIT is a technological park conceived as a space destined to the industrial concentration offering all the common facilities, including a common energy generation system. The energy system is a hybrid installation comprised of a trigeneration plant (with diesel engine) and a photovoltaic and thermal solar plant. The combined system was intended to fulfill all the energy needs of the buildings in the industrial park: electrical power, cooling, heating and sanitary hot water as well as the electrical needs of the University campus close to it. All the installations of energy generation have been situated in a common zone, from where electricity and thermal energy are distributed.

Several reasons as the increase in the energy demand of the TechPark and the University; the price of the electricity in Spain and; the already available connection to the main grid, changed the operation strategy. This made necessary to develop a new concept of management for the energy system.

The ParcBIT project is framed in a more extensive project called “Pla BIT segle XXI” [22]. Its goal is to offer to professionals, companies and institutions an area provided with all the facilities and services required by the companies based in the information technologies. This area takes up 140 hectares located near Palma, the capital of Mallorca, and next to the University of Balearic Islands.

2.2 Generation resources

2.2.1 CHP units

The plant comprises two CATERPILLAR diesel gensets [23], with an electric power output of 1.45 MVA and a thermal power output of 1.24 MW by motor. The waste heat of the engines is recovered as heated water at 95°C and it is used for warming water for heating and sanitary warm water and cooling water for refrigeration by an absorption process.

2.2.2 Absorption chillers

The cooling demand is covered by means of two TRANE simple effect absorption chillers [24] by Lithium Bromide, one of 1.32 MW with a COP=0.64 and the other of 436 kW with a COP=0.64. The heat required by the absorption chillers comes from the solar thermal plant and from the CHP plant.

2.2.3 Auxiliary equipment for cooling

If there is an excess of cooling demand and the absorptions chillers do not produce enough cooling power to cover it, two vapor compression cooling centrals [25] have been installed, providing an extra 1.17 MW. The refrigerant in the cooling central is R-134a.

2.2.5 Solar thermal collectors

864 m^2 of high temperature solar thermal collectors are installed. The solar thermal plant [26] is composed of 72 collectors, where each collector has an effective surface of 12 m^2. This plant produces, in summer, water at 95°C, this water is sent to the heat water distribution system. The return water is at 87°C. In winter, the temperature is 90°C and the water return is at 87°C. The nominal flow is 63 m^3/h. These collectors were installed by the company ARCON. The inclination angle of the panel is of 30° south-oriented. This angle was the optimum result in the simulation carried out within the TRNSYS program [27]. See on figure 1.

2.2.6 Photovoltaic plant

A photovoltaic plant of 8.6 kWp feeds power to the minigrid. The photovoltaic park is divided into three array fields. Each of the fields consists of 24 monocristaline silicon modules, model A-120, of 120 Wp designed and constructed by the firm ATERSA [28]. One inverter per array field model TAURO PR-3000/8 is installed. These inverters have a nominal power output of 2.4 kW.

Figure 1: PV and solar thermal panels

2.2.7 District heating and cooling system

A network of pipes distributes the hot and chilled water to supply the thermal demand of the minigrid. There is a 400 m^3 general storage tank for hot water, as well as other two tanks for hot water and two tanks for cold water of 100 m^3 each. From the tanks (excluding the general tank), cold and hot water is distributed via a main pipe of 19.90 km long that is insulated and buried with a leak detection system.

2.2.8 Electricity Distribution in the minigrid

The minigrid is interconnected with the main grid at a 66 / 15 kV transformer.

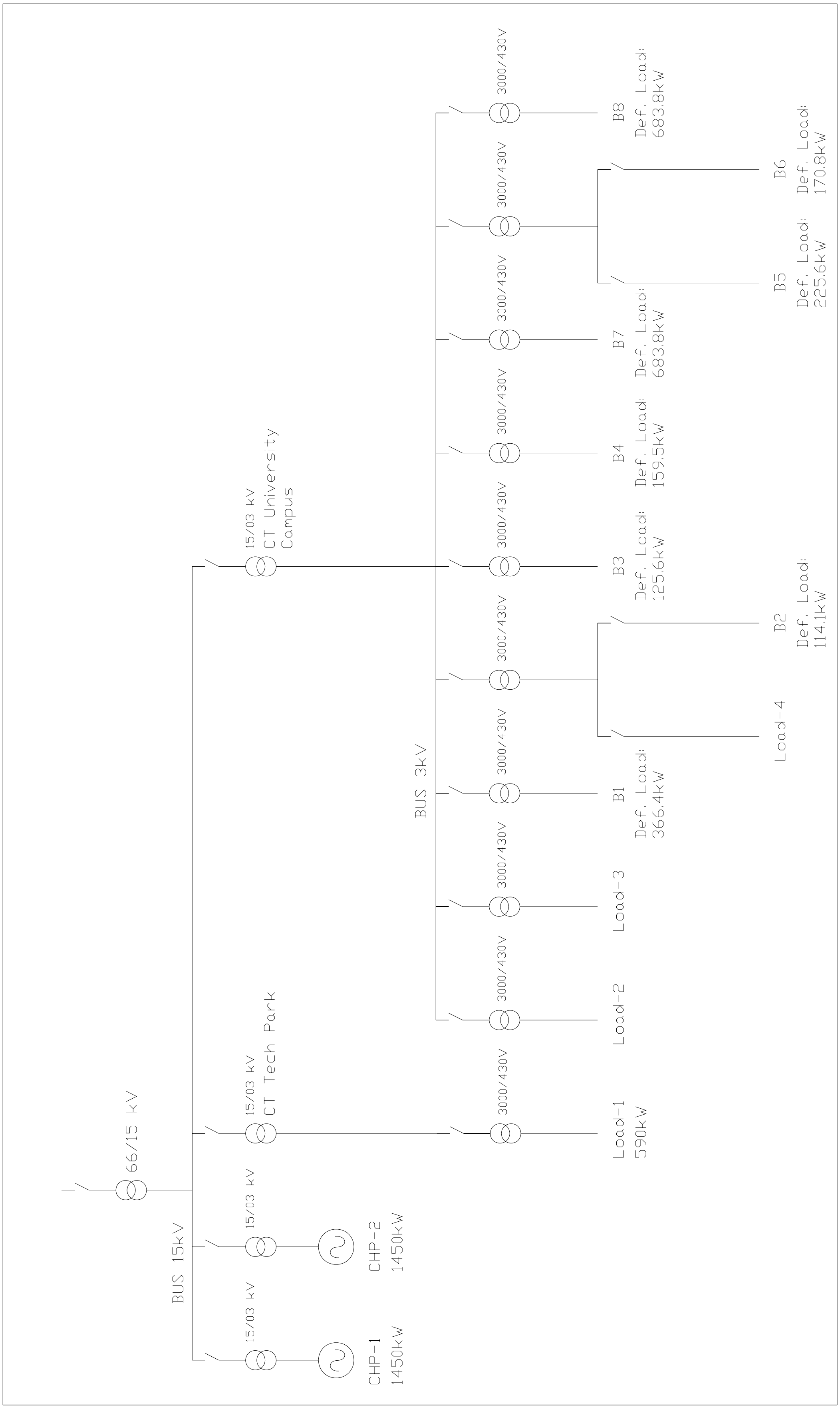


Figure 2: Minigrid's unipolar diagram

On figure 2 the distribution grid of the minigrid is shown. The distribution grid in the University Campus is formed by nine transformer centers connected in ring configuration. The total installed power in deferrable loads is 2529.6 kW; the total installed generation is 2900 kW in CHP units and 8.6 kWp of photovoltaic. The description of deferrable loads is discussed later on.

2.3 Installed Power

2.3.1 Classification of loads

According to their function, the consumers in a building will be classified in two main categories: non-deferrable loads and deferrable loads. The non-deferrable loads are those which can not be rescheduled without affecting the comfort of the users. On the contrary, the deferrable loads are those which can be rescheduled without affecting the users' comfort.

After defining the overall consumption, the different origins of this consumption must be identified in order to determine the deferrable and non-deferrable fractions. In this work four main groups of electrical loads have been identified. Three of them are considered as non-deferrable and one of them as deferrable.

Main groups of electricity loads:

- *Fixed load:* electrical loads which are related to the basic centralized services of the University and Tech Park, e.g. emergency services, security, servers,…

- *Lighting:* the different buildings' lighting as well as the general lighting of streets.

- *Non-deferrable due to activity:* the electricity necessary for PC's and other equipment necessary for developing the activity.

- *Deferrable load:* the load of large centralized air conditioning and heating devices.

2.3.2 Deferrable Loads - Equipment description

The deferrable loads considered in this work are large centralized air conditioning/heating devices. These devices are located in 8 large buildings and provide the energy for cooling and heating those buildings, see on table 1.

TABLE 1: Power installed in the minigrid's large AC devices

BUILDING NUMBER	BUILDING NAME	POWER INSTALLED Kw	NUMBER OF DEVICES
B1	Anselm Turmeda	366.4	2
B2	Guillem Colom	114.1	2
B3	Aulario experimentos	125.6	2
B4	Son Lledó	159.5	2
B5	Comedor central	225.6	4
B6	Beatriu de Pinos	170.8	3
B7	Guillem Cifré	683.8	4
B8	Jovellanos	683.8	4
Total		2529.6	23

2.4 Energy Consumption

2.4.1 Global energy consumption in the studied minigrid

The minigrid considered in this work is formed by a cluster of buildings, including Offices and a University campus.

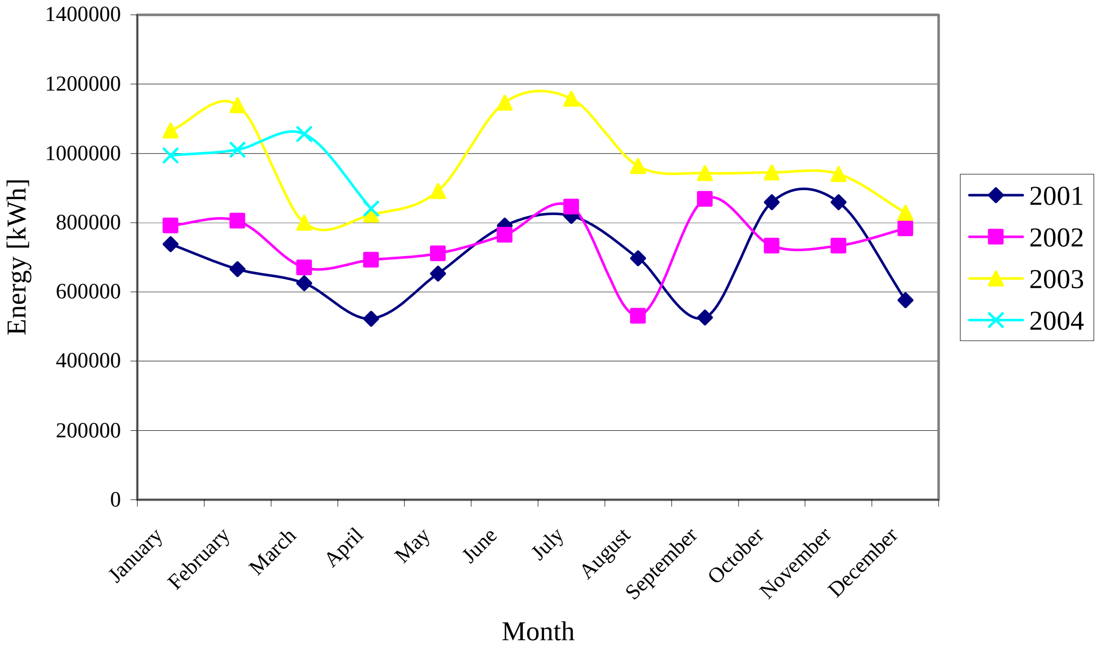


Figure 3: Four years minigrid's electrical consumption

The data about the overall consumption of the minigrid for the last four years is given in figure 3. The Tech Park was constructed on 2002 and it began its operation on February 2003. This is the reason of the sudden increase in the energy consumption from 2002 to 2003.

From figure 2.3, two peaks can be identified; the summer peak and the winter peak. Both electricity peaks are consequence of the use of electricity in heating and air conditioning systems. In April, it can be considered that all centralized air conditioning and heating systems are off. August is a holiday month in Spain, therefore its electricity consumption has not been taking into account.

2.4.2 Identification of energy consumption origin

The minigrid's energy consumption is divided in two main consumers: the University campus and the Tech Park.

Identification of energy consumption in the University campus

The identification of the origin of the energy consumption in different kind of buildings has been a matter of many studies. In the case of University buildings, one of those studies was carried out by the Official Energy Statistics from the U.S. Government [29]. The result of this study performed on 327 University Buildings all around U.S. showed a standard distribution of energy consumption, which can be seen on figure 4.

Figure 4: Typical values for energy consumption in University buildings

It is important to emphasize that this study is valid only for the campus' buildings and therefore a study for the campus' common facilities and lighting is made later on.

Identification of energy consumption in the Tech Park

The Tech Park is a concentration of Office Buildings; no industry has production in this Tech Park. Many studies have been performed in the identification of energy consumption sources in office buildings. Some of these studies have been performed by governmental offices [30], [31] and other by universities in research projects [32], or private companies [33].

The results of these studies are similar to each other, but a study on 100 Swiss offices [34] seemed to be the most complete. The result of this study is given in figure 5.

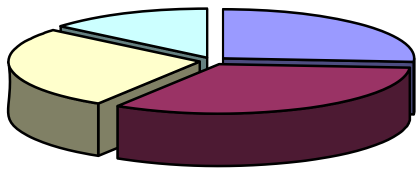


Figure 5: Typical values for energy consumption in Office buildings

The aim of this point is to identify the deferrable consumption, in this case no deferrable loads are installed in the Tech Park, both heating and cooling is provided by the district network. Therefore, all the energy consumption in the Tech Park will be due to lighting, Office equipment and others.

In the case of our Tech Park the space heating and cooling is provided by a district heating and cooling network, it means that the electricity consumption is only due office equipment, lighting and others. It means that a new distribution in the energy consumption must be done, respecting the same percentage: 45% office equipment and central services; 36% Lighting; 19% Ventilation.

Data from Mallorca

On Mallorca, however, there is no study about the energy consumption in the University or Office buildings. Nevertheless, studies about the energy consumption in households have been performed by the Balearic Government [35]. The results of these studies indicate a similar distribution of the energy consumption, see on table 2.4.

TABLE 2: Comparison of energy consumption per activity

	UNIVERSITY [%]	OFFICE [%]	MALLORCA HOUSEHOLDS [%]
Space heating and cooling	37	26	35
Water Heating	N.A.	N.A.	26
Lighting	22	27	9
Office equipment and central services	N.A.	33	N.A.
Ventilation	N.A.	14	N.A.
Others	41	N.A.	31

The main consumption components are space heating and cooling and lighting in our case. The other consumptions depend on the activity.

The main difference between households and Office and University buildings is lighting. The reason could be that the illumination level in a household is lower than the one in a University due to the activity. A higher illumination would impact in higher

energy consumption. Another reason could be the use of the lighting, in offices and Universities the lighting is on during the activity.
The consumption in space heating and cooling is comparable in the three cases.

2.5 Case Study: February 2004

In the next chapters the management system for our minigrid will be developed. In order to test this energy management system a representative case has been chosen. Because of it is the month with higher deferrable load consumption, February was chosen. From the data provided the most recent was from the year 2004.

2.5.1 Energy consumption measurements

The data obtained from the measurements of the energy meters installed in the minigrid, is referred to three main periods in the day. All the days in the month are divided in three different fixed periods: peak hours; valley hours and flat hours. The distribution of the periods during the day depends on the time of the year: if we are in the summer time or winter time, see on table 3.

TABLE 3: Three Periods Metering system

During Winter time	Peak hours	from 18 until 22 (4 hours every day)
	Valley hours	from 1 to 9 (8 hours every day)
	Flat hours	the rest (12 hours every day)
During Summer time	Peak hours	from 19 to 23 (4 hours every day)
	Valley hours	from 1 to 9 (8 hours every day)
	Flat hours	the rest (12 hours every day)

The data of the energy meters installed in the minigrid corresponding to each metering period is given in table 4.

TABLE 4: Energy Consumption in the minigrid for February 2004 (I)

ENERGY METER	ACTIVE ENERGY				REACTIVE ENERGY	MAXIMETER
	Flat	Peak	Valley	Total		
	[kWh]				[kVAr]	[kW]
UIB	398172	213085	337511	948768	204124	2370
Tech Park	36406	11714	13969	62089	54525	184

2.5.2 Previous considerations

In order to identify the energy consumption of the deferrable loads and non-deferrable loads, some previous considerations must be done before starting this classification.

Solar radiation

For identifying the schedule of the general lightings the information of solar radiation for February 2004, see on figure 2.6.

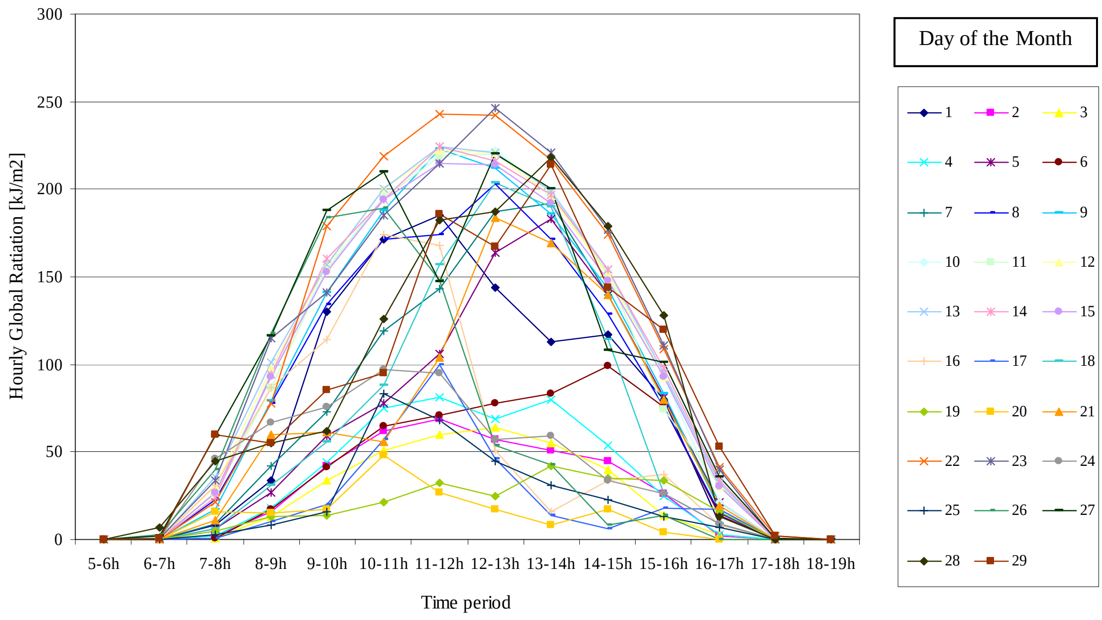


Figure 6: Global radiation during February 2004

The schedule for the general lighting has been considered from 16h until 8h, for every day in February 2004, it means sixteen hours every day.

Schedule for working days

February 2004 had 29 days: 20 working days and 9 weekend days. The University starts at 8:00 and finishes lectures at 21:00. The offices in the Tech Park start at 8:00 and finish at 18:00.

Data from available Energy meters installed in the minigrid

Two energy meters have been installed in the University, one in the general campus lighting and one in the main server room. The data provided in February 2004 is as follows:

General campus lighting	=>	24060kWh
General server	=>	3781 kWh

2.5.3 Identification of energy consumption origin

Fixed load (E_{fixed})

While the fixed load of the Tech Park ($E_{fixed,Techpark}$) was not available, it was assumed to be the same proportion from the overall consumption in the Techpark ($E_{overall,TechPark}$) as in the University campus ($E_{fixed,University}$ / $E_{overall,University}$).

$$E_{fixed,TechPark} = E_{overall,TechPark} \cdot \frac{E_{fixed,University}}{E_{overall,University}} = 62089kWh \cdot \frac{3781kWh}{948768kWh} = 247.43kWh$$

The fixed load is constant distributed for every day (29d), every hour (24h) during February 2004. The University Campus: 5.43 kWh every hour. The Tech Park: 0.36 kWh every hour. See the distribution of energy consumption for the metering times during the moth on table 2.7.

Lighting

The lighting is formed by two main components: the general lighting of the Campus and of the streets in the Tech Park and the lighting during the day.

1.- General lighting ($E_{GenLighting}$)

The general lighting in the University campus ($E_{GenLighting,Uni}$) and in the Tech Park ($E_{GenLighting,TP}$) was switched in February from 16h until 8h.

$$E_{GenLighting,TP} = E_{overall,TP} \cdot \frac{E_{GenLighting,Uni}}{E_{overall,Uni}} = 62089kWh \cdot \frac{24060kWh}{948768kWh} = 1572.89kWh$$

The consumption in General lighting per hour that the lighting is on is given as follows for the University campus ($E_{GenLighting,Uni/hour}$) and for the tech Park ($E_{GenLighting,TP/hour}$):

$$E_{GenLighting,Uni/hour} = \frac{E_{GenLightig,Uni}}{D \cdot H} = \frac{24060kWh}{29 \cdot 16} = 51.85kWh/h$$

$$E_{GenLigthing,TP/hour} = \frac{E_{GenLightig,TP}}{D \cdot H} = \frac{1582.89kWh}{29 \cdot 16} = 3.41kWh/h$$

where:

D – number of days the general lighting is on during February 2004
H – number of hours every day the general lighting is on during February 2004

The results of the energy consumption in general lighting are given in table 2.7.

2.- Buildings lighting ($E_{BuiLighting}$)

The energy consumption in buildings can be calculated with the overall consumption minus general lighting minus fixed consumption. The distribution of the energy consumption (see on point 2.4.2) is referred to the buildings energy consumption ($E_{Buildings}$) of the University campus, 22% in this case, and the Tech Park, 36% in this case, see on table 2.7.

Non-deferrable due activity ($E_{nonDeferrable}$)

As in the buildings lighting the value is referred to the $E_{Buildings}$. It includes in the University campus 41% related to others, such as PC's or services. In the Tech Park, it includes 45% of the general consumption in Office equipment and central services, including PC's and 19% in ventilation.

Deferrable

1.- Total deferrable ($E_{T\text{-}Deferrable}$)

Deferrable loads are those loads related to the air conditioning and heating devices. In the Tech Park, the whole energy consumption in heating and cooling is provided by the district heating and cooling, non electricity devices have been installed. In the University campus all the energy consumption is due to the work of electricity devices and it corresponds to the 37% of the $E_{Buildings}$, see results on table 5.

TABLE 5: Energy Consumption in the minigrid during February 2004 (II)

	$E_{overall}$	E_{fixed}	$E_{GenLighting}$	$E_{Buildings}$	$E_{BuiLighting}$	$E_{nonDeferrable}$	$E_{T\text{-}Deferrable}$
University							
Flat	398172	912.24	7518.25	389741.51	85743.13	159794.02	144204.36
Peak	213085	304.08	6014.6	206766.32	45488.59	84774.19	76503.54
Valley	337511	1151.16	10525.55	325834.29	71683.54	133592.06	120558.69
Tech Park							
Flat	36406	60.48	494.45	35851.07	12906.39	22944.68	0.00
Peak	11714	41.76	395.56	11276.68	4059.60	7217.08	0.00
Valley	13969	76.32	692.23	13200.45	4752.16	8448.29	0.00

2.- Deferrable in our case ($E_{Deferrable}$)

8 out of 11 buildings in the University have deferrable loads, the other 3 have room heating and cooling distributed devices which are not suitable of being deferred. In order to simplify the problem a simple calculation will be made, 8 buildings represent the 73% of the energy consumption in room air conditioning and heating.

TABLE 6: Energy Consumption in the minigrid during February 2004 (III)

	$E_{overall}$	E_{fixed}	$E_{GenLighting}$	$E_{Buildings}$	$E_{BuiLighting}$	$\boldsymbol{E_{nonDeferrable}}$	$\boldsymbol{E_{Deferrable}}$
University							
Flat	398172	912.24	7518.25	389741.51	85743.13	**198729.20**	**105269.18**
Peak	213085	304.08	6014.6	206766.32	45488.59	**105430.15**	**55847.58**
Valley	337511	1151.16	10525.55	325834.29	71683.54	**166142.90**	**88007.84**
Tech Park							
Flat	36406	60.48	494.45	35851.07	12906.39	**22944.68**	**0.00**
Peak	11714	41.76	395.56	11276.68	4059.60	**7217.08**	**0.00**
Valley	13969	76.32	692.23	13200.45	4752.16	**8448.29**	**0.00**

Therefore, the deferrable load will be the 73% of the energy consumption for room heating and cooling in the University and the rest of the $E_{T\text{-}Deferrable}$ will be considered as $E_{nonDeferrable}$. The final distribution for the energy consumption is given in table 6.

TABLE 7: Daily schedule of large AC devices for February 2004

DEVICE			POWER [kW]	HOUR 7	8	9	10	11	12	13	14	15	16	17	18	19	20
B1	*M1*	*C1*	91,6	1	0	0	0	0	1	0	0	0	1	0	1	0	0
		C2	91,6	1	1	0	0	0	0	1	0	0	0	0	1	0	1
	M2	*C3*	91,6	1	0	0	0	0	1	0	0	0	1	0	1	0	1
		C4	91,6	1	1	0	0	1	0	0	0	0	1	0	0	1	0
B2	*M1*	*C1*	58,9	1	0	0	0	0	0	0	0	0	1	0	0	0	0
	M2	*C2*	55,2	1	0	0	1	0	0	1	0	0	1	0	1	0	0
B3	*M1*	*C1*	30,4	1	0	1	0	0	1	0	0	0	0	0	1	0	1
		C2	30,4	1	1	0	1	0	0	1	0	0	1	0	0	1	0
	M2	*C3*	30,4	1	0	1	0	0	0	0	0	0	0	0	1	0	1
		C4	30,4	1	1	0	1	0	0	0	0	0	1	0	0	1	0
B4	*M1*	*C1*	40,0	1	1	1	0	1	0	1	0	0	0	0	0	0	0
		C2	40,0	1	0	0	1	0	1	0	1	0	0	0	0	0	0
	M2	*C3*	35,0	1	1	1	0	1	0	1	0	0	0	0	0	0	0
		C4	35,0	1	0	0	1	0	1	0	1	0	0	0	0	0	0
B5	*M1*	*C1*	28,2	1	0	0	0	0	1	0	0	0	0	0	0	0	0
		C2	28,2	1	1	0	0	0	0	1	0	0	0	0	0	0	0
	M2	*C3*	28,2	1	0	0	0	0	1	0	0	0	0	0	0	0	0
		C4	28,2	1	1	0	0	1	0	1	0	0	0	0	0	0	0
	M3	*C5*	28,2	1	1	0	0	0	1	0	0	0	0	0	0	0	0
		C6	28,2	1	0	0	0	0	0	1	0	0	0	0	0	0	0
	M4	*C7*	28,2	1	1	0	0	0	1	0	0	0	0	0	0	0	0
		C8	28,2	1	0	0	0	0	1	0	0	0	0	0	0	0	0
B6	*M1*	*C1*	70,4	1	1	0	0	1	0	0	0	0	0	0	1	0	1
		C2	70,4	1	0	0	0	0	1	0	0	0	0	0	0	1	0
	M2	*C3*	12,4	1	1	0	0	1	0	1	0	0	0	0	1	0	0
	M3	*C4*	9,9	1	0	0	0	0	1	0	0	0	0	0	1	1	0
B7	*M1*	*C1*	92,8	1	1	0	0	1	0	1	0	0	0	1	0	1	0
		C2	92,8	1	0	0	0	0	1	0	0	0	0	0	1	0	1
	M2	*C3*	92,8	1	1	0	0	0	0	1	0	0	0	1	0	1	0
		C4	92,8	1	0	0	1	0	0	0	0	0	1	0	1	0	0
	M3	*C5*	78,2	1	1	0	0	1	0	1	0	0	0	1	0	1	0
		C6	78,2	1	0	0	0	0	0	0	0	0	1	0	1	0	0
	M4	*C7*	78,2	1	0	0	0	1	0	0	0	0	0	1	0	1	0
		C8	78,2	1	1	0	0	0	1	0	0	0	1	0	1	0	0
B8	*M1*	*C1*	92,8	1	1	0	0	0	0	1	0	0	1	1	0	1	1
		C2	92,8	1	0	0	0	0	1	0	0	0	0	0	1	0	0
	M2	*C3*	92,8	1	1	0	1	0	0	1	0	0	0	1	0	1	0
		C4	92,8	1	0	0	0	0	1	0	0	0	1	0	1	0	0
	M3	*C5*	78,2	1	0	0	0	0	0	1	0	0	0	1	0	1	0
		C6	78,2	1	0	0	1	0	1	0	0	0	1	0	1	0	0
	M4	*C7*	78,2	1	1	0	0	0	0	1	0	0	0	1	0	1	0
		C8	78,2	1	0	0	1	0	0	0	0	0	1	0	1	0	0

From the $E_{Deferrable}$ and the information about when the different devices are operating, the schedule for those devices has been developed (refer to table 7). The only building which will have the air conditioning and heating devices working 24 hours is building B3. This building has different laboratories, in which experiments are running the whole night.

Table 7 is divided into three main sections. The first section corresponds to the description and location of the devices (composed of number of Building, number of the Machine and number of the Compressor). The second section is the nominal power of each device. The third section is the schedule (0- the compressor is off; 1- the compressor is on).

2.5.4 Hourly Load Profile for a typical working day of February 2004

With the information provided in the points above, the hourly energy consumption has been obtained. Figure 7 shows the graphic representation of the presented results.

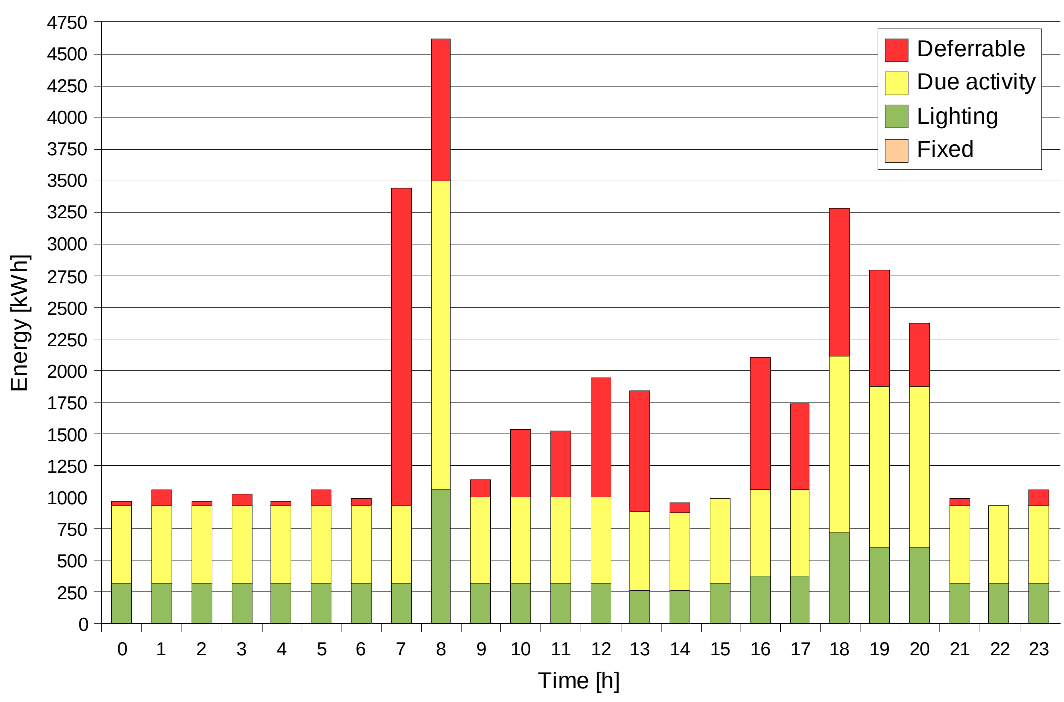


Figure 7: Minigrid's daily energy consumption for February 2004

2.6 Response capability of the studied Minigrid

2.6.1 Previous concepts

Before identifying the different types of loads several concepts must be clarified.

Building Thermal Mass Concept

For the last years several investigations have been preformed in using the thermal capacitance of buildings for decreasing operation costs in maintaining comfort conditions in the building sector. Four main opportunities in reducing costs have been detected: reduction in demand costs; use of low cost off-peak electrical energy; reduced mechanical cooling resulting from the use of cool night-time air for ventilation pre-cooling; and improved mechanical cooling efficiency due to increased operation at more favorable part-load and ambient conditions [36]. The translation of this research in real applications is placed in standard systems as e.g. free-cooling systems; pre-cooling systems, some of them even regulated by local laws and converted in obligation e.g. the Spanish regulation in matter of free-cooling systems [37]. However, the application of these methods is mainly being done by large industrial buildings and not directly applied to clusters of buildings.

The proposal of this work is to use this capability of thermal storage in buildings for reducing the peak- electricity load when the price of the electricity in the Energy Market is high and increasing it when lower.

Load Shedding technologies

There are two main technologies for load shedding.
The first one would be to act on the control system of the equipment. This first technology can be done in a direct way, communicating the energy management system with the control system of the device, and indirectly acting on the sensors.
The second one would be to shut on and off the electricity feeding of the device.
Directly communicating with the control system would be the first choice, although this is not always possible. Therefore the other two possibilities have been also considered.

2.6.2 Deferrable loads- capacity

As conclusion of the last point, the deferrable electricity load capacity of our minigrid in figure 2.8 is given.

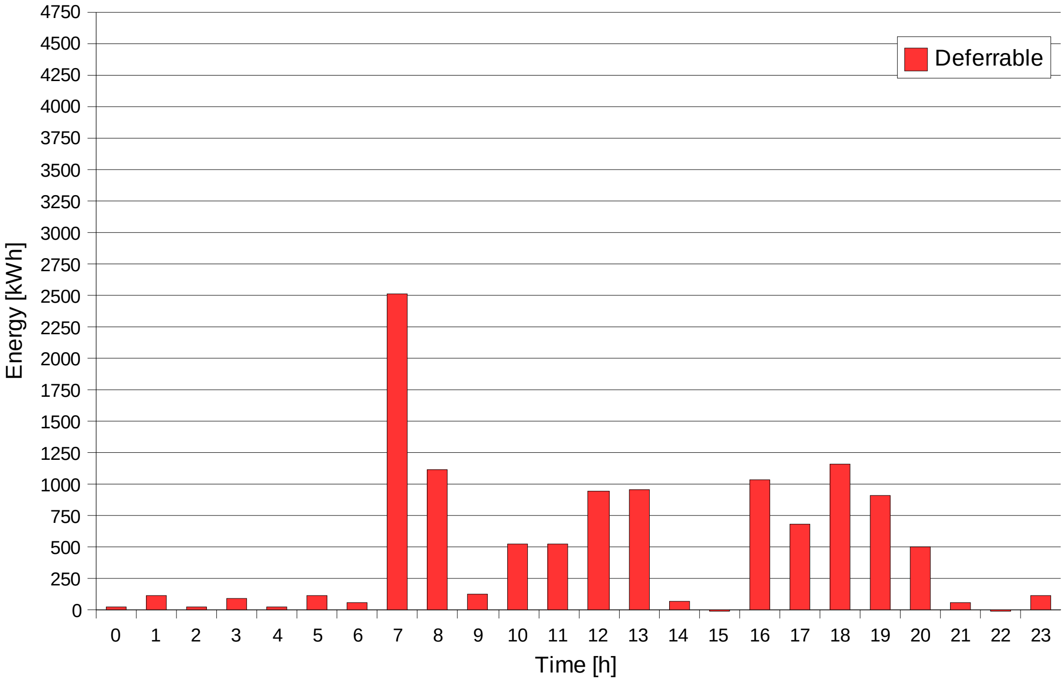


Figure 8: Deferrable Electricity load capacity for a typical day of February 2004

2.6.3 Time Delay: Buildings thermal storage capacity

The potential for storing thermal energy within the structure and furnishings of conventional commercial buildings is significant when comparing to the load requirements. Typically, internal gains are on the order of 0.11-0.12 kWh (100 frig/m2) per square meter of floor space. The thermal capacity for typical concrete building structures is on the order of 2–4 Wh/°F per square foot of floor area (12– 24 Wh/°C-m2). Thus, for an internal space, the energy storage is on the order of 1 hr for every °F ~0.5°C of precooling of the thermal mass [38]. That approximation can be explained by a deeper knowledge of the differential equations which represents the energy fluxes between a building and its environment, this explanation is based on reference [39].

The heat fluxes between different bodies can be studied by using the following set of differential equations:

$$\rho c \frac{\partial T}{\partial t} = div(\lambda grad(T)) = div\left(\lambda \begin{pmatrix} \frac{\partial T}{\partial x} \\ \frac{\partial T}{\partial y} \\ \frac{\partial T}{\partial z} \end{pmatrix}\right)$$

$$\Rightarrow \frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

In the case of buildings, the heat transfer function between a building and its environment has been considered in an only dimension, that means:

$$\frac{\partial T}{\partial y} = \frac{\partial^2 T}{\partial y^2} = \frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial z^2} = 0$$

It reduces the problem of the heat transmission to the solution of a single equation:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\rho c}\frac{\partial^2 T}{\partial x^2}$$

A way to find a numerical solution to this problem is the discretisation of the wall in small Δx for every Δt, and consider boundary conditions.

Depending on the complexity of the problem the calculation of the boundary temperature can be manually done or with a finite elements software. The evolution of the temperature function of the time in every Δx for every Δt can be considered as:

$$\frac{\partial T(n\Delta x,k\Delta t)}{\partial t} = \frac{T(n\Delta x,k\Delta t + \Delta t) - T(n\Delta x,k\Delta t)}{\Delta t} = \frac{T_{n,k+1} - T_{n,k}}{\Delta t}$$

And, therefore:

$$\frac{\partial^2 T(n\Delta x, k\Delta t)}{\partial x^2} =$$
$$= \frac{1}{\Delta x}\left(\frac{T(n\Delta x + \Delta x, k\Delta t) - T(n\Delta x, k\Delta t)}{\Delta x} - \frac{T(n\Delta x, k\Delta t) - T(n\Delta x - \Delta x, k\Delta t)}{\Delta x}\right)$$
$$= \frac{1}{\Delta x^2}\left(T_{n+1,k} + T_{n-1,k} - 2T_{n,k}\right)$$

The differential equation in the case of buildings (one dimension) results in:

$$\frac{T_{n,k+1} - T_{n,k}}{\Delta t} = \frac{\lambda}{c\rho}\frac{1}{\Delta x^2}\left(T_{n+1,k} + T_{n-1,k} - 2T_{n,k}\right)$$

The walls are not build up of homogeneous material but different layers of different materials, the different in the conduction capacity of these materials is not negligible.

For example, in the case of a wall build up with two different layers, the differential equation takes up the following shape:

$$T_{l,k+1} = \frac{\Delta t}{\Delta x^2}\left(a_2\left(T_{l+1,k} - T_{l,k}\right) - a_1\left(T_{l,k} - T_{l-1,k}\right)\right) + T_{l,k}$$

Being a_1 and a_2 both coefficients depending on the conductivity of the material λ [W/mK], the density ρ [kg/m^3] and thermal capacity c [kWh/kgK].

$$a_i = \frac{\lambda_i}{c_i \rho_i}, i = 1,2$$

Taking into account, convection and conduction heat transfer, where α is the air convection factor [W/m^{2}K]:

$$T_{0,k+1} = T_{0,k} + \frac{\Delta t}{\Delta x \rho \ c}\left(\alpha\left(T_{Raum} - T_{0,k}\right) - \frac{\lambda}{\Delta x}\left(T_{0,k} - T_{1,k}\right)\right)$$

A roughly simplification of this calculation (considering no loses) is used by civil engineers in order to calculate the minimal thermal isolation requirements for a building:

$$\frac{Qtotal}{t} = \alpha 1 \cdot S(text - tp1) = \lambda 1 \cdot S \cdot \frac{Tpext - T1}{L1} = \lambda 2 \cdot S \cdot \frac{T1 - T2}{L2} = \lambda 3 \cdot S \cdot \frac{T2 - Tpint}{L3} = \alpha 2 \cdot S(tp2 - tint)$$

The main actors in the heat transfer calculations are shown in figure 9.

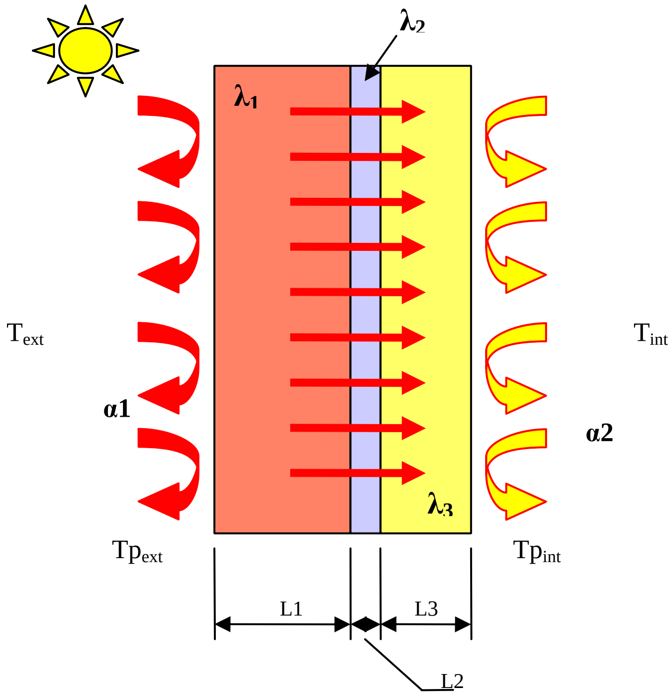


Figure 9: main actors in the heat transfer equation

Being:

α_1: external wall air convection coefficient
$\lambda_{1,2,3}$: conduction coefficients, of the different materials conforming the wall
α_2: internal wall air convection coefficient

The thermal exchange between building and outside is mainly related to these coefficients and to the thickness and surface of the layers.

The time it takes to the building to decrease or increase its temperature is function of the above described parameters. This time is matter of different studies which objective is to set up an Energy Management System able to make the maximal profit of it, using this capacity of energy storage of the building.

As example, the result of one of the studies carried out by the University of Kassel. This experiment consisted in the study of two different kind of heating systems, heating the building and recording the time it takes to completely discharge the building (Text-Tint=0°C), depending on the external temperature. The characteristics of the studied building and the initial temperatures are giving in the reference [40].

As a matter of approximation, in our minigrid a discharge time constant of our buildings of 0.5°C/every hour has been assumed, although it would depend on external temperatures, solar radiation and wind, as well as furniture inside the building.

CHAPTER 3

DESCRIPTION OF THE CLUSTER MANAGEMENT SYSTEM

The Cluster Management System (CMS) is an energy management system suited for including the minigrid in a new concept of control, where issues such as economical profit and stability coexist with new concepts like grid support and market-driven platform.

3.1 CMS levels

The CMS is defined in three different and independent levels, regulated by the main grid necessities, see on figure 10.

The first level is the default control mode of the minigrid. Its aim is to optimize the operation cost by making use of the Spanish Electrical Day-ahead Market.

The second level is a grid support operation level. This level is activated by a drop in the main grid's frequency. In order to helping in the stabilization of the main grid, the minigrid decreases its incoming power flow from the main grid or even increases its outgoing flow to the main grid. This level is regulated by a bilateral contract with the transportation grid operator, in this case REE[1].

The third level is an emergency mode operation. The CMS switches to emergency level when high stability problems are detected, such as a blackout in the main grid.

[1] Red Electrica Española

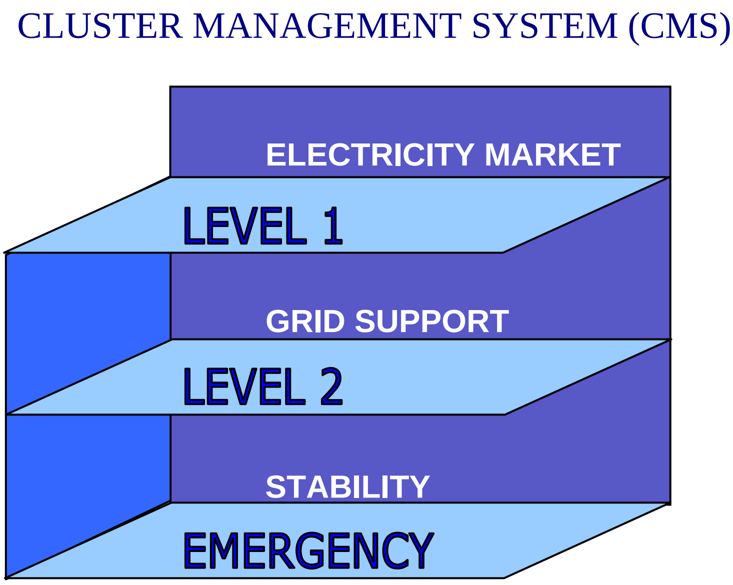


Figure 10: CMS levels

3.2 Boundaries of the System

Resuming Chapter 2, our CMS has been applied on a minigrid which generation plant is composed by CHP units, solar photovoltaic panels, solar thermal collectors, absorption chillers and water storage tanks. The load is formed by two main consumers: a University Campus and an industrial park. The connection between plant and consumer is done through an electrical grid and a district heating and cooling network. This implies that both thermal and electrical energy flows take place.

3.2.1 Constrains

For the correct operation of the system (consumers, plant and main grid) some behavioural characteristics have been defined. To begin with, the plant is aimed to supply the thermal energy requirements (heating or cooling as necessary) of the consumers connected to the district heating and cooling network.

Due to the high share of CHP units in the plant, the production of electricity is strongly related to the thermal demand. The produced electricity is then supplied to the consumer loads which could be deferrable and non-deferrable, see on chapter 2.

The existence of thermal storage elements in the plant adds another degree of freedom that could be used for matching the thermal demand.

Also, the minigrid can work either isolated or connected to the main grid. Its state depends on whether the plant is able to balance the whole electrical demand of the consumers. When this cannot be reached, the minigrid purchases or sells the unbalance from or to the main grid. One of the main focuses in the development of the management of this minigrid is to maximize the economical benefit of this transaction.

Based on the mentioned behaviour, the above objective could be accomplished by handling the available degrees of freedom of the system in a manner that could maximize its economical viability. In the proposed energy management system, this is done by coupling the scheduling of the dependable energy sources to the country's energy market and to the forecast of the consumer needs.

The mathematical description of these constrains is given in the next chapter.

3.2.2 Connecting to the Spot Market

There is no unique model of an energy market; however, some characteristics are recurrent in most of the models being currently used. At the heart of these energy markets is an auction which is used to determine the daily generation and consumption of energy. While there has been some debate as to what market design the day-ahead and real-time auctions should take [41], the fact is that these auctions determine the price of the electricity throughout the day.

The CMS subject of this work considers the following market design: There is a system operator which establishes a security-constrained, day-ahead and intradaily spot markets for energy in the form of auctions. Although in the work of our CMS only the day-ahead market has been considered. Both markets, the day-ahead and the intradaily work independently. Bids and offers in the day-ahead market occur during one hour and define the hourly price of the subsequent day period, 24 hours before the price enters in validity. Bids and offers in the intradaily market are being made throughout the day.

An example of this kind of design is the Spanish energy market, which operator is OMEL[2] [42]. Specific rules regarding to the connection with it are defined by the operator via its website. In order for the studied CMS to participate in the market, the minigrid operator must be registered as an Agent. After paying the registration fee, the daily market price information is received via ftp by the minigrid operator. The decision algorithms are explained in the following chapters. An added value in the case of the Spanish Electrical Market is that it shows a consistent price pattern over time, which makes price forecasting a reasonable prospect of success [43].

3.3 The Spanish Energy market

The liberalization process began in Spain the 27th November of 1997 with the approval of the law 54/1997 [44]. This law regulates the activities related to the energy supply, including generation, transport, distribution, merchandising and international exchanges, as well as economical and technical management of the electrical system.

Two companies are in charge of the correct function of this infrastructure: The Operator of the Market called OMEL and; The Operator of the System called REE. The Operator

[2] Operador del Mercado Eléctrico Español

of the Market is responsible for the economical management of the system and the Operator of the System is responsible for the technical management of it.

The Spanish market is organized in two independent pool based markets with common rules. The first one is the daily market; it matches the day-ahead consumption forecast of the system with the production. The second one is the intradaily market; its object is to adjust the set point defined in the daily market to the behaviour of the system during the day. A deeper description of the daily market is provided in the next paragraphs [45]. In our CMS only the day-ahead market has been considered.

3.3.1 The price of the electricity

In the liberalized environment the price of the electricity is different for every hour. The final price for an hour is the sum of the estimation of three different terms:

- The final price of the electricity in the feeder of the power station
- The Toll of the energy transportation and distribution
- The Taxes are three: taxes due to the construction of power stations (3,04% this year), tax on the electricity (defined by the government) and the VAT[3].

In the case that the consumer buys electricity from a commercial agent or by a bilateral contract with a supply company, the prices will not be based on the above described terms. Nevertheless, the final price will be somehow related to the hourly price in the energy market.

3.3.2 Day-ahead Market

The daily market is a day-ahead market. It is organized on an acquisition-sell offers based platform.

The process starts and the System Operator (REE) sends to the Market Operator (OMEL) the following information:

- Last demand forecast
- Available energy units
- Interconnections maximal capacity

The last demand forecast is the estimation of the whole system demand for a given day D, it is available in the System Operator's website.

The information about the available units in the system is a relation of generation units (known by generation units those elements in the system able to produce electricity) which are not able to produce electricity during this daily market session for different reasons: breakdowns, annual revisions, recharge of fuel (in the case of nuclear power stations). All the units in the system which are not included in this list are obligated to present an offer in the daily market. The only production units which are not obligated

[3] Value Added Tax

to present offer to the daily market are those called the special regime producers. The special regime producers are the distributed facilities, including renewable energy sources, connected with the main grid. Due to the limit in the exchange capacity in the interconnection with other electrical systems from other countries, the operator of the system set this boundary condition to the electrical exchange.

Before 10:00 of the day D the different agents send their offers to the Market Operator (OMEL). The offers reception for the day D+1 ends at 10:00 of the day D.

The match process between sell offers and buy offers begins. After the first matching, the Market Operator applies the boundary conditions sent by the System Operator and verifies the viability of the result.

The Operator of the Market carries out a second matching, where the final price is established. The Operator of the System with this information and the bilateral contracts and special regime producers establishes the final hourly program.

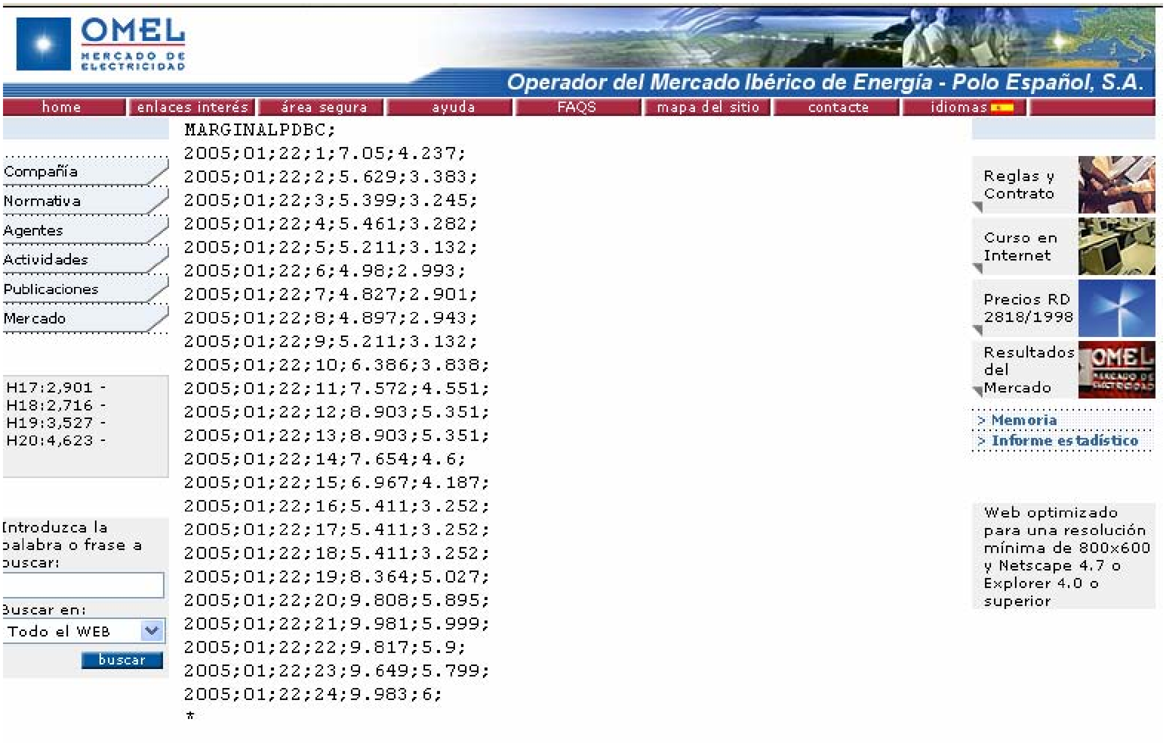


Figure 11: Electricity prices published on the Market Operator website. Day 22.1.2005

The final result of the price for the day D+1 is published at 11:00 of the day D in the Market Operator website [46]. The final hourly program is published by the System Operator.

The information on the Market Operator website can be download as a text file via ftp connection, see on figure 11.

TABLE 8: Energy Generation Data in the Spanish system *(Source: REE)*. Day 22.1.2005

ELECTRICAL BALANCE (MWh)	SATURDAY, THE 22 OF JAN OF 2005				
	Day	*Month*	*Incr % Month*	*Year*	*Incr %Year*
Hydropower	39.621	1.170.714	-53,12	1.170.714	-53,12
Nuclear	187.748	4.111.935	2,45	4.111.935	2,45
Coal	223.620	5.085.632	20,13	5.085.632	20,13
Natural Gas	82.344	2.672.253	131,36	2.672.253	131,36
Fuel – Oil	4.167	516.204	169,04	516.204	169,04
------------------------------	-------------	----------------------	-----------------	-----------------	--------------
TOTAL GENERATED	537.500	13.556.738	12,12	13.556.738	12,12
Consumption for generation	-25.135	-630.296	26,21	-630.296	26,21
Special Regime producers (*)	147.200	3.146.160	5,48	3.146.160	5,48
------------------------------	-------------	----------------------	-----------------	-----------------	--------------
NETO GENERATION	659.565	16.072.602	10,28	16.072.602	10,28
Pumping consumption	-14.282	-355.627	20,48	-355.627	20,48
Internacional connection	17.337	236.409	-	236.409	-
TRANSPORTATION DEMAND	662.620	15.953.384	13,02	15.953.384	13,02
Incr Dem. Corr. (**) %	-	-	11,81	-	11,81
Losses in transportation	7.568	192.990	-12,76	192.990	-12,76
DISTRIBUTION DEMAND	655.052	15.760.394	13,43	15.760.394	13,43

(*) Including the ones with prima - (**) Corrected by temperature and work activity

The information on the System Operator website can also be download from its website as a excel table, see on table 8 [47].

3.3.3 Bidding in the Day-ahead Market

The offers are hourly. Every offer is composed by 25 different sections and every section composed by a pair quantity/price, see on table 3.2. When the offer is to sell electricity the section must be organized by decreasing prices. When the offer is to acquire electricity the sections must be organized by increasing prices. The limits in the price are defined by the Market Operator.

After the matching of the different offers to sell and to acquire electricity, the price of the electricity for every hour will be known.

In all the sections, every offer for acquiring electricity which price is lower than the price hour of the matching; its quantity of electricity will be adjudicated at the matching price. In all the sections, every offer for selling electricity which price is higher than the price hour of the matching; its quantity of electricity will also be adjudicated at the matching price.

TABLE 9: Three sections acquisition offer from 1 until 13 hours *(Source: OMEL)*

	Hour												
Section 1	1	2	3	4	5	6	7	8	9	10	11	12	13
Energy	165	132	165	165	165	165	150	165	132	165	165	180	165
Price	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
	Hour												
Section 2	1	2	3	4	5	6	7	8	9	10	11	12	13
Energy	20	33	20	20	20	20	20	20	33	20	20	20	20
Price	0,1	0,02	0,2	0,2	0,2	0,2	0,2	0,1	0,02	0,2	0,2	0,2	0,2
	Hour												
Section 3	1	2	3	4	5	6	7	8	9	10	11	12	13
Energy	25	20	20	20	20	20	20	25	20	20	20	20	20
Price	0,2	0,3	6,5	6,5	6,5	6,5	6,5	0,2	0,3	6,5	6,5	6,5	6,5

As example, in table 9 the matching process for hour 2, if the result is 0,1, the amount of electricity obtained is 53 kW.

3.3.4 Matching demand and offer

Matching demand and offer is the main purpose of the Operator of the Market. The matching process can be simple or complex.

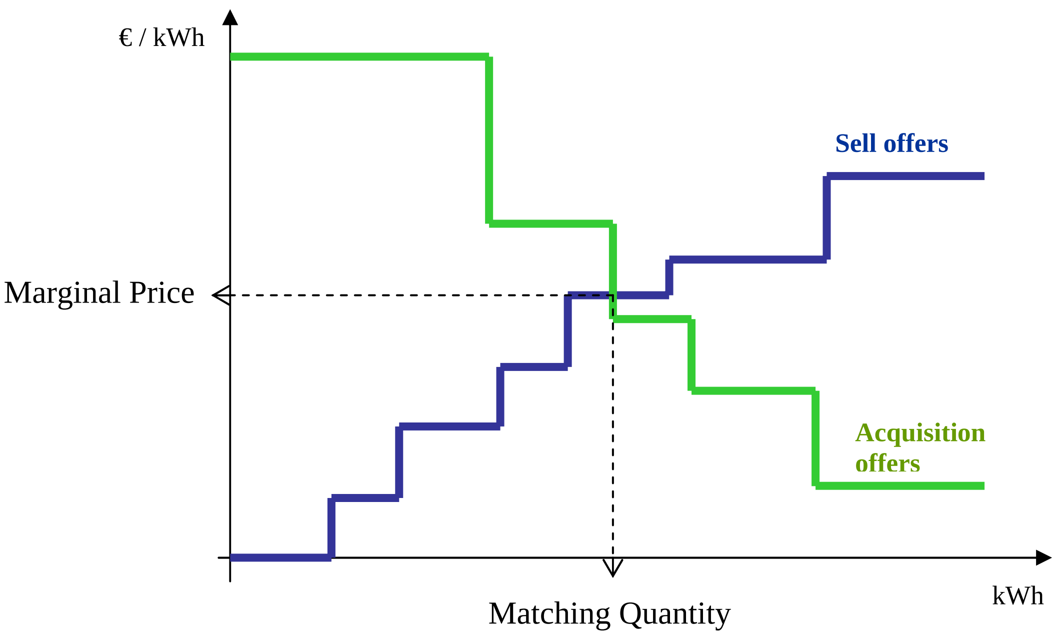


Figure 12: Simplified matching process for acquisition and sell offers

Simple matching process takes into account only sell offers and acquisition offers, see on figure 3.3.

The complex matching process takes also into account conditions of indivisibility, for example a big turbine can not produce half of the energy of its nominal power without decreasing its yield.

3.3.5 Liberty margin of the system

The system is structured in such a way that the price remains quite constant even when the bids are very different. This fact is due to the price limits established by the Operator of the Market, boundary conditions given by the Operator of the System and quite constant electricity production and demand of the different agents involved.

3.3.6 Prices variability in the market

After assessing the limited liberty margin of the system, a conclusion can be given: assuming that the price shows a high stability, there is a relationship between price and day of the year. With a data base of the last years'marginal prices of the market this relationship has been researched.

The assumption we made was that for foreseeing the price one day ahead, we could use the same price for the same day the week before. In order to prove this assumption, the ratio between the middle price for one week and the middle price for the week before was calculated. The middle price was defined as two different variables, middle price of the working days during the week and middle price of weekend for every week in the year.

Middle Price of the labour days:

$$M_X^W = \frac{\sum_{i=\{labour\_days\}} M(i)}{\sum_{i=\{labour\_days\}} 1}$$

Knowing:

M(i) = Medium value of the electricity marginal prices for the day i
Being i a real value between 1 and 5
M^W_X = Medium value for the week of the year,
Being X a real number between 1 and 52.

Data base with the marginal prices for every hour every day in the year is provided in Annexe 1.

$$Ratio1 = \frac{M_{(X-1)}^W}{M_X^W}$$

Ratio1 evolution can be seen in figure 13.
Middle Price of the weekend days:

$$M_X^{WE} = \frac{\sum_{i=\{weekend\_days\}} M(i)}{\sum_{i=\{weekend\_days\}} 1}$$

Knowing:

M(i) = Medium value of the electricity marginal prices for the day i
Being i a real value between 1 and 2

$M^{WE}{}_X$ = Medium value for the week of the year,
Being X a real number between 1 and 52.

Data base with the marginal prices for every hour every day in the year is provided in Annexe 1.

$$Ratio2 = \frac{M_{(X-1)}^{WE}}{M_X^{WE}}$$

Ratio2 evolution can be seen in figure 14.

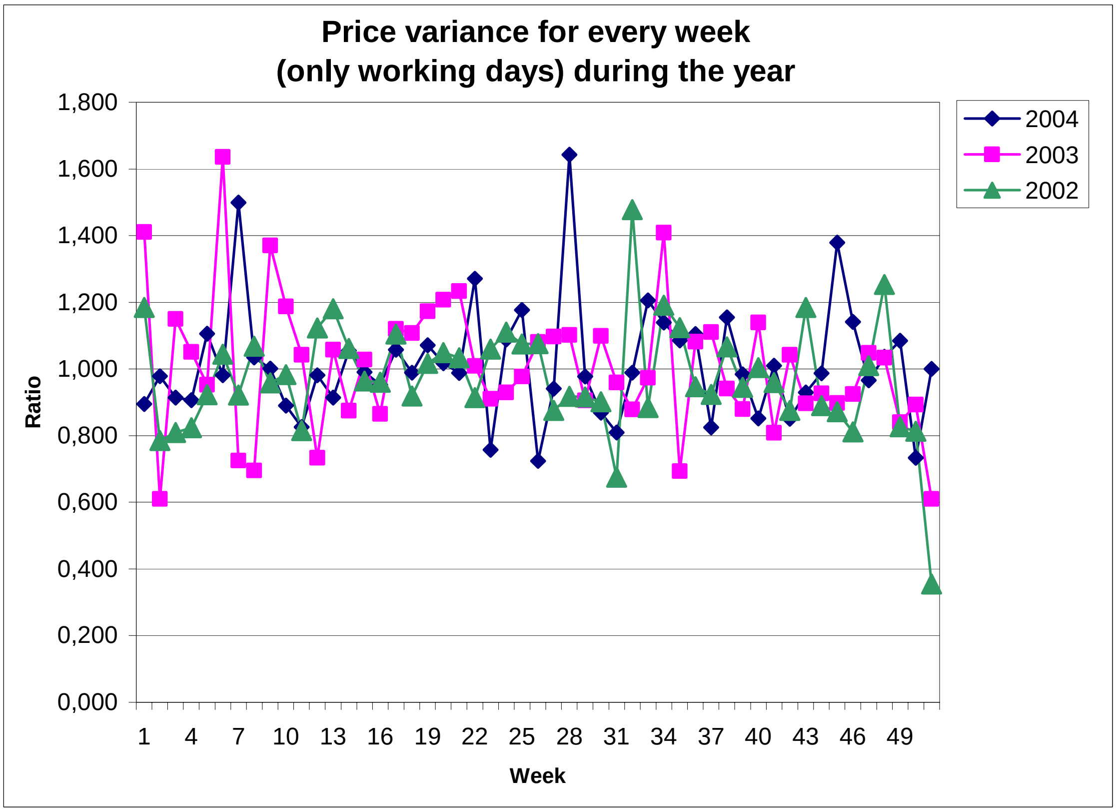


Figure 13: Ratio one week middle price by week ahead middle price

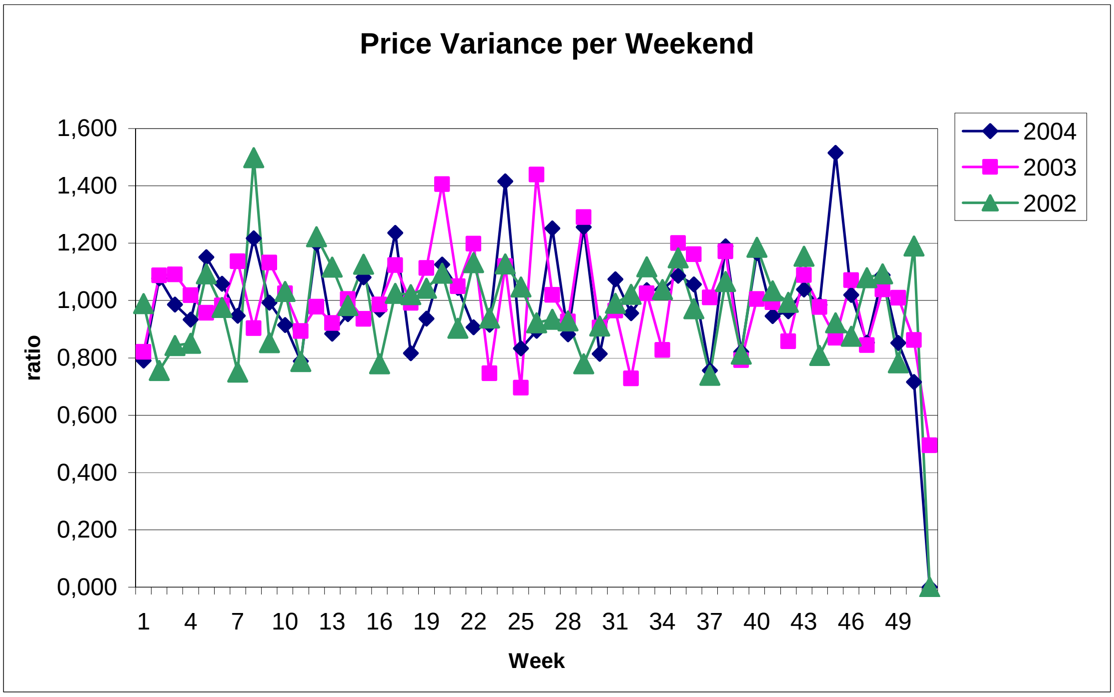


Figure 14: Ratio one weekend middle price by weekend ahead middle price

The conclusion is that the calculated ratio moves around 1. Therefore, for the forecast algorithm the input of prices of the electricity will be taken as the same price of the same day the week before.

3.3.7 Deviation of the forecast versus the electricity consumption

The deviation is the difference between the day-ahead forecast of the electricity consumption made and the real electricity consumption during the day. This detour can turn out to be an excess of electricity or a deficit. In both cases the market agent is not penalized, in the case of an excess the agent does not pay the electricity bought but not consumer. In the case of a defect in the electricity forecast, the electricity consumed is invoiced at the market price. The bill provided will content two different annotations, the first one is the electricity consumption at the market price, the second one is the price of the overcost for the system because of this defect or excess of electricity.

CHAPTER 4

CMS FIRST LEVEL

The objective of this control level is to optimize the cost of the minigrid operation, using the different price-hour pairs of the energy market and the ability of the minigrid to defer loads.

Before 10:00 the bid in the day-ahead market must be done. Before the bidding starts, the schedule of the plant must be defined. This schedule is developed running an optimisation algorithm, which takes into account the different parameters of the minigrid, as well as the forecast of prices. This chapter's objective is to describe all the actors taking part in this process: parameters, variables and constrains; optimisation algorithm and developed software for the CMS first level.

4.1 Parameters in the optimisation

The optimisation algorithm is based in minimising the addition of the costs variable for every hour. For calculating the cost variable is necessary to carry on an electrical and thermal energy balance and an hourly cost balance. The Constants in out system are known and a set of Known Variables will be calculated before to start the optimisation.

Costants in our System:

$A[kW_{th}]$ – Nominal thermal power of the CHP units
$B[kW_{e}]$ – Nominal electrical power of the CHP units

Known Variables:

Pf [€/ltre] – Price of the fuel used by the CHP units
Pe(t) [€/kWh_e] – Price of the electricity in the energy Market
C(t) [kWh_{th}] – Production of the solar thermal collectors
T(t) [kWh_{th}] – Thermal demand of the buildings connected to the district heating
E(t) [kWh_e] – Production of the solar photovoltaic panels
F(t) [kWh_e] – Electrical Non-Deferrable Load
H(t) [kWh_e] – Electrical Deferrable Load
P_O – Operation Cost of the Minigrid
$P_{O\&M}$ – Maintenance Cost of the Minigrid
P_I – Insurance cost of the Minigrid
D – Days in which the Minigrid is in operation during the month
$P_u(t)$ – Price of the electricity sold to the University and to the Tech Park
$P_v(t)$ – Price of the electricity sold to the Grid
$P_{T(t)}$ – Price of the thermal energy sold to the Tech Park

Unknown Variables:

G(t) [kWh_e] – Electricity Input from the main grid
X(t) [%] – Load of the first cogenerator
Y(t) [%] – Load of the second generator
Z(t) [kW_{th}] – storage of thermal energy
Om(t) [%] – part of the deferrable load which is going to be fulfilled
cost(t) [€] – cost of the plant operation plus electricity purchases

Energy Balance :

1.- Thermal balance:
A·X(t) + A·Y(t) + Z(t-1) + C(t) = T(t) + Z(t)
2.- Electrical balance:
B·X(t) + B·Y(t) + E(t) + G(t) = F(t) + w(t)·H(t) + (1-w(t-1))·H(t-1)

Cost & Benefits:

$$Cost(t) = \begin{cases} G(t) > 0 & G(t)\cdot P_v(t) + \dfrac{P_O + P_I}{12\cdot D\cdot 24} + (P_{O\&M} + Pf\cdot E_{ff})\cdot B\cdot (X(t)+Y(t)) - \\ & - P_T\cdot T(t) - (F(t) + w(t)\cdot H(t) + (1-w(t-1))\cdot H(t-1))\cdot P_u \\ & \\ G(t) \le 0 & \dfrac{P_O + P_I}{12\cdot D\cdot 24} + (P_{O\&M} + Pf\cdot E_{ff})\cdot B\cdot (X(t)+Y(t)) - P_T\cdot T(t) - \\ & - (F(t) + w(t)\cdot H(t) + (1-w(t-1))\cdot H(t-1))\cdot P_u - G(t)\cdot Pe(t) \end{cases}$$

Constraints to our system:

1.- Limit in the energy storage capacity
Calculation:
Storage tank capacity: V = 400m3

Specific water heat at 80ºC: Cp = 4.197 kJ/(Kg·K) [26] = 0.00116 kWh/(Kg·K)

Maximal Energy storage capacity:

$$E = Cp \cdot V \cdot T = 0.00126 \cdot 400000\text{ltres} \cdot (80\text{-}60) = 9326 \text{ kWh}$$

Hypotesis: 80ºC (impulsion)
60ºC (return)

Constraint 1:

$$0 \leq Z(t) \leq 9326 \text{ kWh}_{th}$$

2.- Maximal electrical input
Maximal capacity of the interconnection with the main grid.

Constrain 2:

$$|G(t)| \leq 2750\text{kW}$$

3.- Load range of the CHP units
From the characteristic parameters of the CHP units the efficiency line can be drawn, see on figure 15. A decrease in the efficiency can be observed when approaching to 50% load. Therefore, it is assumed that our units will not work in ranges below 60%.

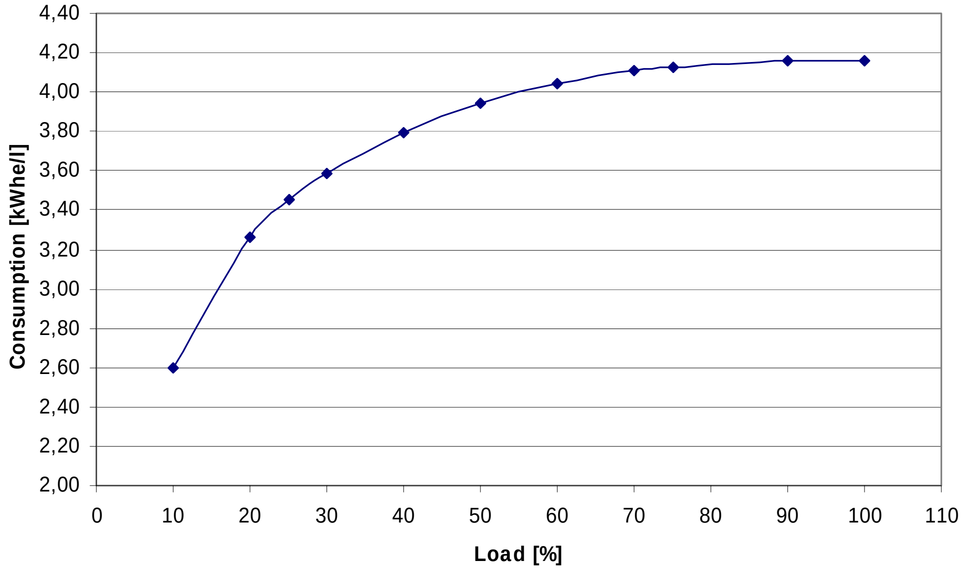


Figure 15: Efficiency line of the CHP units

Constrain 3:

$$60 \leq X(t) \leq 100$$
$$60 \leq Y(t) \leq 100$$

<u>Optimisation of the system:</u>
The optimisation consists in minimizing the daily cost:

$$\sum_{t=1}^{24} Cost(t) = \min$$

In the next paragraphs the different Known Variables are defined:

4.1.1 Pf [€/ltre] – Price of the fuel used by the CHP units

The fuel used by the CHP units is Diesel and its price will depend on the contract with the supply company.
In the software provided this variable is one of the inputs that has to be given, the default value will be 260€/m3, which is the price available in the chosen minigrid.

4.1.2 Pe(t) [€/kWh$_e$] – Price of the electricity bought in the energy Market

The price in the energy market will be known after the cassation between offers and demands and after applying the restrictions of the system, therefore there is no possibility of knowing it before the bids are made.

In chapter 3, we made an assumption and prove an assumable error for this assumption. The assumption was that the price in the energy market in Spain shows a quite stable pattern. Consequently, we assumed that the price for a day would be similar to the price of the same day the week before.

4.1.3 C(t) [kWh$_{th}$] – Production of the solar thermal collectors

The solar thermal collectors field is formed by 72 units grouped in Strings of two collectors connected in an Array. Every solar collector has an effective surface of 12.5m^2. The orientation of each collector is south with an inclination of 30ºC. The total effective surface of the solar plant is 900m^2.

Design temperatures of the solar field:

Summer mode:	T_1 = 87ºC	T_2 = 95ºC
Winter mode:	T_2 = 87ºC	T_2 = 90ºC

The solar collector performance:

$$\eta = 0.78 - 3.5\frac{(T_m - T_L)}{E} - 0.002\frac{(T_m - T_L)^2}{E}$$

Where:

T_m – mean fluid temperature [ºC]
T_L – Ambient air temperature [ºC]
E – Irradiance [W/m^2]

The equation for calculating the performance of the solar collector Arcon Solvarme A/S (1999). Technical note Ref. M0140gb. Arcon HT Solar collector. Skorping, Denmark.

4.1.4 T(t) [kWh_{th}] – Thermal demand of the buildings connected to the district heating network

The dynamic thermal demand of the different buildings connected to the district heating and cooling network has been defined by applying simulations tools. In this case the software TRNSYS is the tool used for that [48].

The models of the different buildings have been defined and after with the inputs of the meteorological forecast the calculations are made.

4.1.5 E(t) [kWh_e] – Production of the solar photovoltaic panels

Because of the low impact of the photovoltaic panels in the minigrid energy production, it has been disregarded.

4.1.6 F(t) [kWh_e] – Electrical Fixed Load

The fixed loads are defined as the loads which can not be deferred. The way to define this loads has been explained in chapter 2.

4.1.7 H(t) [kWh_e] – Electrical Deferrable Load

As in point 4.1.6, the information necessary for identifying the deferrable loads has been explained in chapter 2.

4.1.8 P_O, $P_{O\&M}$, P_I – Operation Costs of the Minigrid

Operation Cost (P_O) [€/year]	Maintenance ($P_{O\&M}$) [€/kWh]	Insurance (P_I) [€/year]
160000[1]	0,01314[1]	13000[1]

4.1.9 D – Operation Days of the Minigrid

Days during the month that the Minigrid is operating

[1] Data provided by the minigrid operator for the year 2004

4.1.10 $P_u(t)$, $P_{T(t)}$ – Price of the Energy sold to the Customers

Thermal energy Price $P_{T(t)}$	Electricity Price $P_u(t)$		
	Flat	Peak	Valley
[€/kWh]	[€/kWh]	[€/kWh]	[€/kWh]
0,0600[1]	0,062986[2]	0,1070762[2]	0,0359020[2]

4.1.11 $P_v(t)$ – Price of the Energy sold to the Grid Operator

The electrical energy remaining after covering the necessities of the University and the Tech Park is sold to the main grid.
The price of this energy, $P_{S2}(t)$, is calculated as per the Spanish corresponding regulation, Real Decreto 436/2004[3] [49].

$$P_{S2}(t) = P_e(t) + Bonus + Incentive$$

Where:

Bonus = n * T

Where: n= 0.3 during the first 10 years
n= 0 after

Incentive = 0.1*T

The T parameter is defined every year, as example the value for 2004 was 0.0072072€/kWh [50].

4.2 Optimisation Algorithm

The optimisation algorithm is based on Dijktstra's algorithm idea for finding the Shortest Path through a Weighted Graph.

4.2.1 Dijkstra's Algorithm

This Algorithm tries to find the shortest path between two points in a cloud of points. This algorithms method consists in to put labels on a growing number of vertices. A label on a vertex v will have two parts: a length L(v) and a pointer back to another vertex. L(v) represents the length of the shortest known path (to date) from a to v, and the pointer shows the vertex that precedes v on that path [51]. At each step it calculates every possible movement inside the cloud of points and chooses the shortest. In our case the length is the cost of the step. In this way, it automatically rules out the too expensive ways. At the end we will have the cheapest possibility of running the two generators with the variables described before.

[2] Price in the regulated market for 2004

[3] There was a regulation before: the RD 2818/1998, of 23 de December. Although, this one does not take into account the possibility of participating in the Energy Market [50].

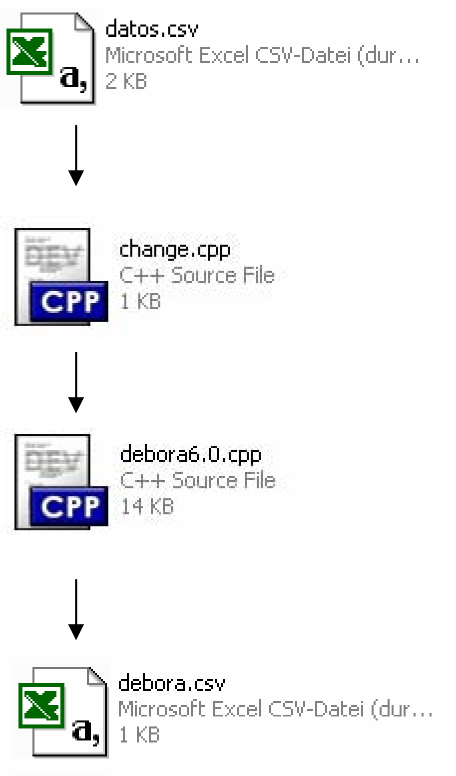
4.2.2 Optimisation program

The optimisation was programmed in C++. This was the best option taking into account that the data arrays were of variable extension.

4.3 CMS first level

The parameters in the optimisation and the algorithm are the basis to construct the CMS level one software.

This software is composed by four different units, explained in figure 16.



Data input: the data input to the C++ program is a data sheet with the list of constants in our system and known variables.

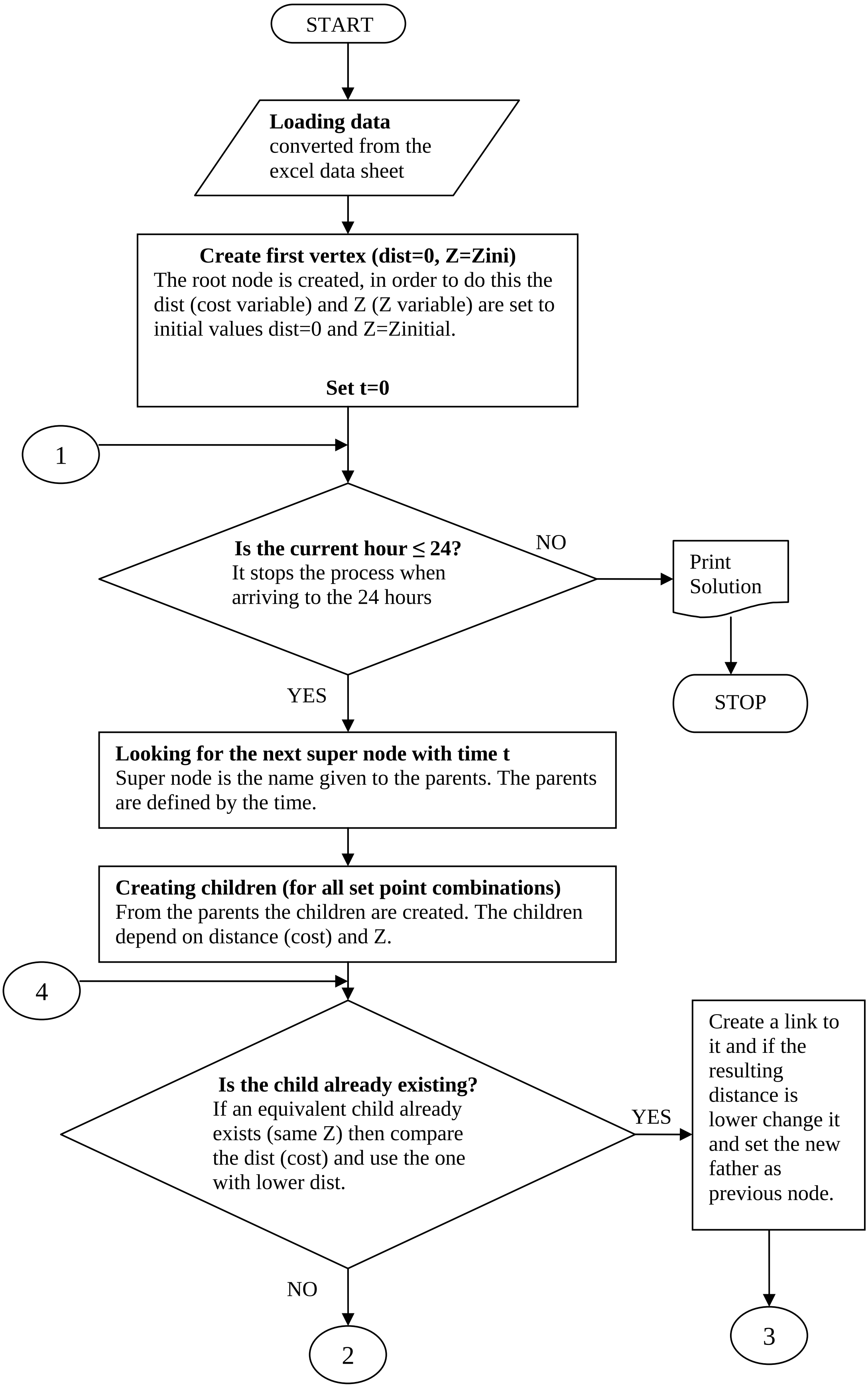
This small C++ utility transforms the excel data sheet in an input file for the program.

This C++ module runs the optimisation algorithm in order to obtain optimal values for the unknown variables.

Data output: The data output of the C++ module is written in an excel table in order to prepare a data sheet for directly bidding in the Energy Market.

Figure 16: CMS first level organisation

The core of the CMS first level is the program called debora6.0. The flowchart of debora6.0 is giving in figure 17.


START
Loading data
converted from the excel data sheet
Create first vertex (dist=0, Z=Zini)
The root node is created, in order to do this the dist (cost variable) and Z (Z variable) are set to initial values dist=0 and Z=Zinitial.
Set t=0
1
Is the current hour ≤ 24?
It stops the process when arriving to the 24 hours
NO
Print Solution
STOP
YES
Looking for the next super node with time t
Super node is the name given to the parents. The parents are defined by the time.
Creating children (for all set point combinations)
From the parents the children are created. The children depend on distance (cost) and Z.
4
Is the child already existing?
If an equivalent child already exists (same Z) then compare the dist (cost) and use the one with lower dist.
YES
Create a link to it and if the resulting distance is lower change it and set the new father as previous node.
NO
2
3

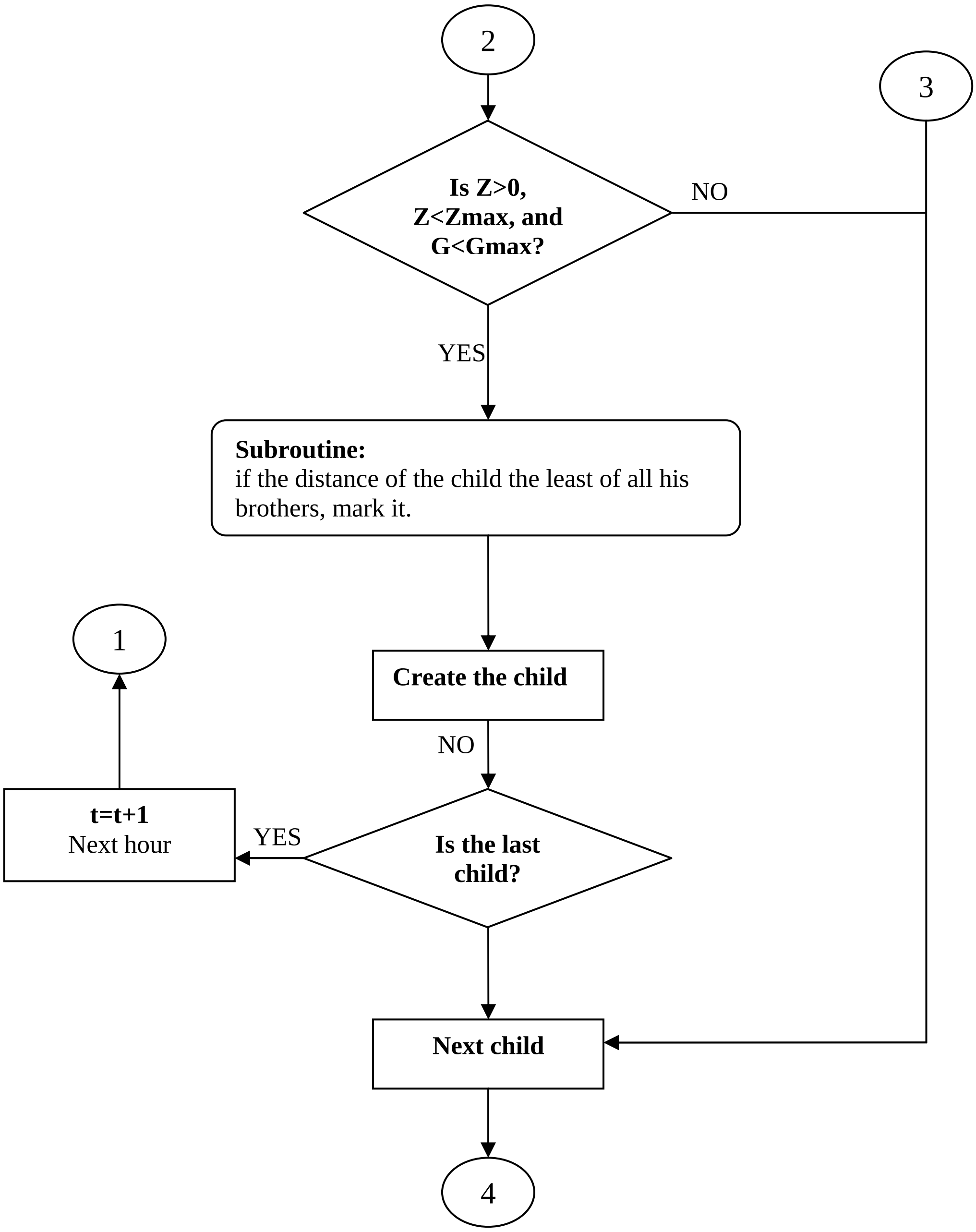


Figure 17: CMS first level flowchart

CHAPTER 5

CMS SECOND LEVEL

In the CMS second level the philosophy of the control system switches from indirectly demand response methods to direct. This change purposes helping the main grid means a quick reaction to frequency drops [52].

This chapter begins with a small description of the necessary basic concepts in order to understand the work of the CMS second level. After that, the operation parameters of this CMS control level are the necessary tool for developing the software. The developed software is given in Annex II, the flowchart to understanding it is the last point in this chapter.

5.1 Basics on Power Systems control

Basic concepts on power systems control can be found in many electrical engineering handbooks, such as [53], [54], [55] and specially [56]. In this chapter only the control related to the main grid operation has been studied. The control of the generators is detailed in chapter 7 and Annex III.

5.1.1 Main parameters: Frequency and Voltage

The variables which have to be controlled in a power system are frequency, voltage and quality of wave. These variables do not remain constant due to the continuously variation of the demand, active and reactive.

Since the point of view of the energy user, some variables control requirements are stricter than others. The slow voltage fluctuations can oscillate in a 15% range without much impact on the user. But the frequency has a major impact on the user. The acceptable limits for these variables are defined by the Standard EN 50160 “Voltage characteristics of electricity supplied by public distribution systems”. A resume of this standard is provided in table 10.

TABLE 10: EN 50160 Main Supply Voltage Phenomena

Supply voltage phenomenon	Acceptable limits	Measurement Interval	Monitoring Period	Acceptance Percentage
Grid frequency	49.5Hz to 50.5Hz 47Hz to 52Hz	10 s	1 Week	95% 100%
Slow voltage changes	230V ± 10%	10 min	1 Week	95%
Voltage Sags or Dips (≤1min)	10 to 1000 times per year (under 85% of nominal)	10 ms	1 Year	100%
Short Interruptions (≤ 3min)	10 to 100 times per year (under 1% of nominal)	10 ms	1 Year	100%
Accidental, long interruptions (> 3min)	10 to 50 times per year (under 1% of nominal)	10 ms	1 Year	100%
Temporary over-voltages (line-to-ground)	Mostly < 1.5 kV	10 ms	N/A	100%
Transient over-voltages (line-to-ground)	Mostly < 6kV	N/A	N/A	100%
Voltage unbalance	Mostly 2% but occasionally 3%	10 min	1 Week	95%
Harmonic Voltages	8% Total Harmonic Distortion (THD)	10 min	1 Week	95%

One of the main objectives of the power supply system is to control the active and reactive power fluxes.

The traditional solution to the regulation of the voltage root mean square (RPM) value and the frequency value has been a hierarchic centralised control. Therefore the quality of the wave is a problem which should be solved in a local mode. The control resources used in this regulation can be specific, such as connection or disconnection of condensator / reactance or continuous as a generator regulation. The values of frequency and voltage in an electricity system are linked to the fluxes and balance of active and reactive power in the lines and generators of the system.

In short, an imbalance between reactive power in the system can provoke changes in the voltage in the nodes (interaction QV); and an imbalance between active power in the system provokes a modification in the frequency which can be “felt” in the whole system (interaction Pf). This modification in the frequency can be used for modifying the power output of the generators in the system.

Both mechanism QV and Pf interact since a modification in the node voltage affects to the active power and therefore to the frequency. The main difference between both mechanisms is the time reaction. A control based on QV mechanism is quick; it takes just some seconds to react, even though a control based on Pf can take some minutes due to the inertial forces of the system.

5.1.2 Controlling the power grid

As said before the power grid can be controlled in a centralised hierarchical way and in a uncoupled way. The hierarchical is usually established in three different levels: Level 1 is a plant or local control level; Level 2 is an area control level; and Level 3 is the whole system level.

Level 1 is usually quicker than the level 2. The time reaction of the Pf in level 1 is between 2 seconds and 20seconds and. in Level 2 is between 2minutes and 20seconds. The time reaction of the QV in level 1 is very quick maximum one second. Level 3 considers the optimisation of the whole system which an optimum load sharing. Both control mechanisms take place QV and Pf and the time reaction of the control is higher to 10minutes.

The control elements which are considered basic for the power system are those which can generate/consume active or reactive power on demand, discreetly or continuous. Those elements can be directly controlled or indirectly through another variable such as voltage in a node, speed of a machine or frequency of the system.

The most important control element is the synchronous generator, used for continuous frequency or voltage control. For the control of reactive power, batteries of condensators/reactances in fixed nodes are installed. These condensators/reactances can be drived by electric or electronic switches. The electronic switches used for this application are called flexible alternating current transmission system (FACTS). The idea of the CMS second level is to convert the minigrid in a control element of the power system, also called grid support element.

5.2 CMS Second Level operation

The CMS second level operates when a frequency drop in the main grid is detected. In order to activate this level some operation parameters have been defined.

5.2.1 Operation Parameters

Three parameters are responsible for the operation of the CMS second level:

- Frequency range: range in which the frequency of the main grid is allowed to oscillate.
- Reaction speed: time the CMS waits before reacting when the frequency goes out of its range.
- Time constant: time it takes to the minigrid to switch again the management from second level to first level.

Frequency range, reaction speed and time constant must be defined in a bilateral contract between minigrids- and main grids- operators.

Frequency range

The frequency range must be defined by the main grid operator. Out of this range the system shows a tendency to be unstable.

In the studied case, the typical oscillations of the frequency grid are in the range between 49.85Hz and 50.15Hz. The manual load shedding begins at 49.75Hz after 5min. The automatically load shedding starts at 49Hz.

The frequency limit for the reaction of our system has been defined in order to avoid both load shedding, because of that the limit of operation is 49.75.

Reaction Speed

When the frequency drops below the operation limit, a counter in the CMS second level is activated. This delay in the reaction of our minigrid allows the main grid to be stabilized by itself, if the main grid does not achieve the frequency security range, then the minigrid switches to CMS second level.

The time delay must be defined by the main grid operator. In our case this delay has been considered as 120s. In order to avoid the manual load shedding which starts after 300s.

Time constants

The time constants in our CMS second level define the times after every decision that the CMS waits to see how it affects to the frequency stabilisation. If after this time the frequency is stable the control system switches again to CMS first level.

These times has been defined as follows:

Time it must remain the frequency inside range to start reconnection process: 120s

Time it takes every reconnection in order to avoid instabilities: 60s

5.2.2 Starting CMS second level

Starting the CMS second level is a key stone of this work, because it marks the point where the behaviour of the minigrid changes from indirect to direct demand response method.

The control of the minigrid is continuously monitoring the frequency when a drop in the frequency (frequency ≤ 49.75Hz) is detected a counter is activated. This counter gives 120s to the main grid to be stabilized by itself. After this time, the frequency is checked again, if it remains under security limits the control level of the minigrid switches from first level to second level.

The start of the CMS second level is defined by the flowchart given in figure 18. The software developed is included in the CMS second level software and given in Annex II.

5.2.3 CMS second level flowchart

The CMS second level software is a software which controls the minigrid with the purpose of helping the main grid in the frequency stabilization. This software orders to increase the set point of the minigrid's CHP units when the frequency of the main grid decreases under certain limits, defined in point 5.2.2. After setting the work of the CHP units it will wait a defined time (120s) to see if the main grid recovers. If the main grid recovers then it changes again to the CMS first level operation. If not, the load shedding process begins. The load shedding process operates in different levels of loads (deferrable, non-deferrable, lighting, fixed loads), every level associated to a frequency range (49.70Hz, 49.40, 49.30Hz and 49.00Hz respectively) and a time delay (60s in every case). When the frequency remains up to 49.75 during a defined time (120s) the load reconnecting process starts, the order in the reconnection is inverse to the order in the shedding process. The last decision of the CMS second level will be to switch to first level and then the CHP units will recover the set point defined by the CMS first level.

The explanation of the complete behavior of the CMS second level is defined in the CMS second level flowchart in figure 19. The complete software developed is given in Annex II.

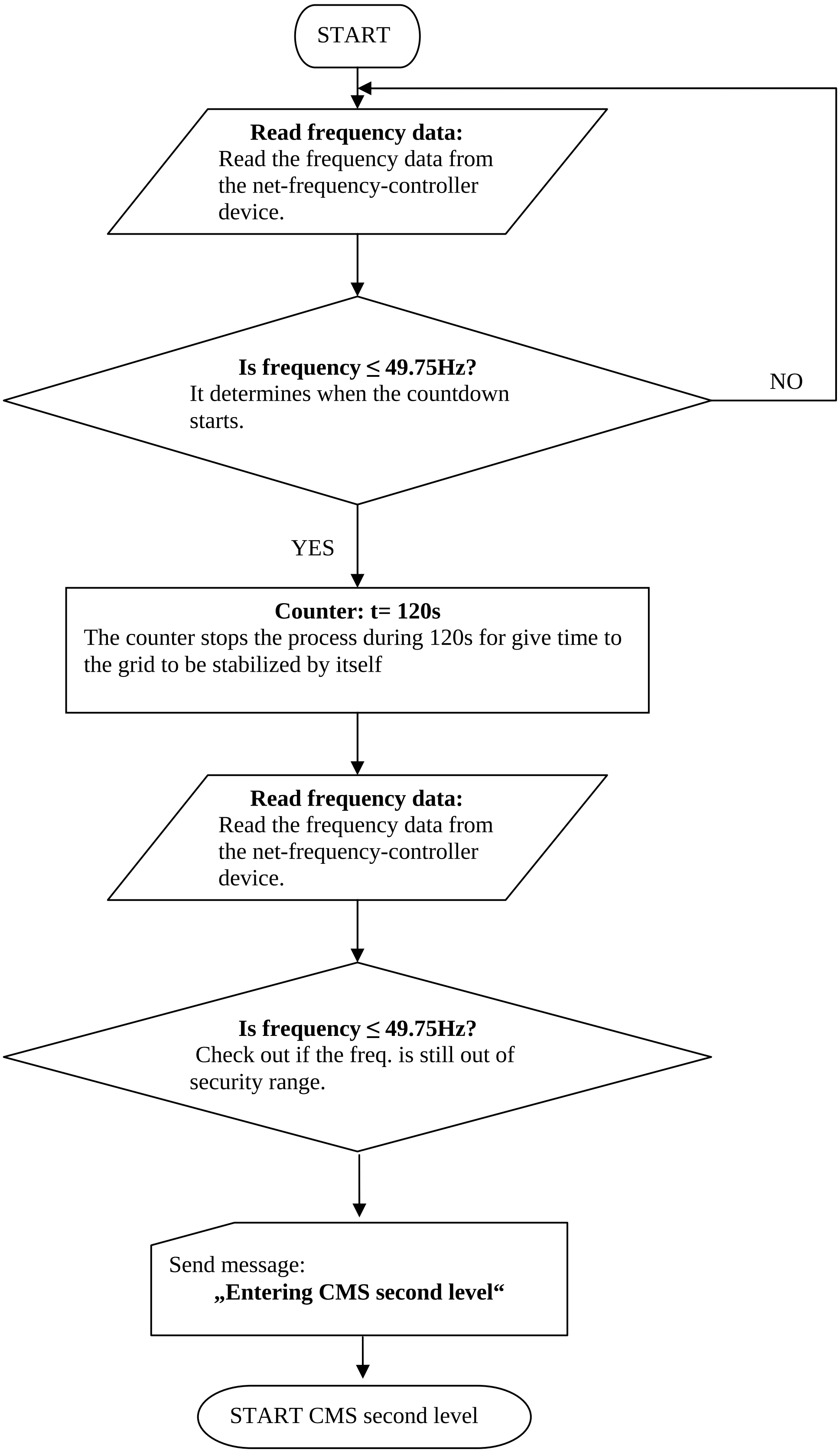


Figure 18: CMS Second Level Flowchart (I)

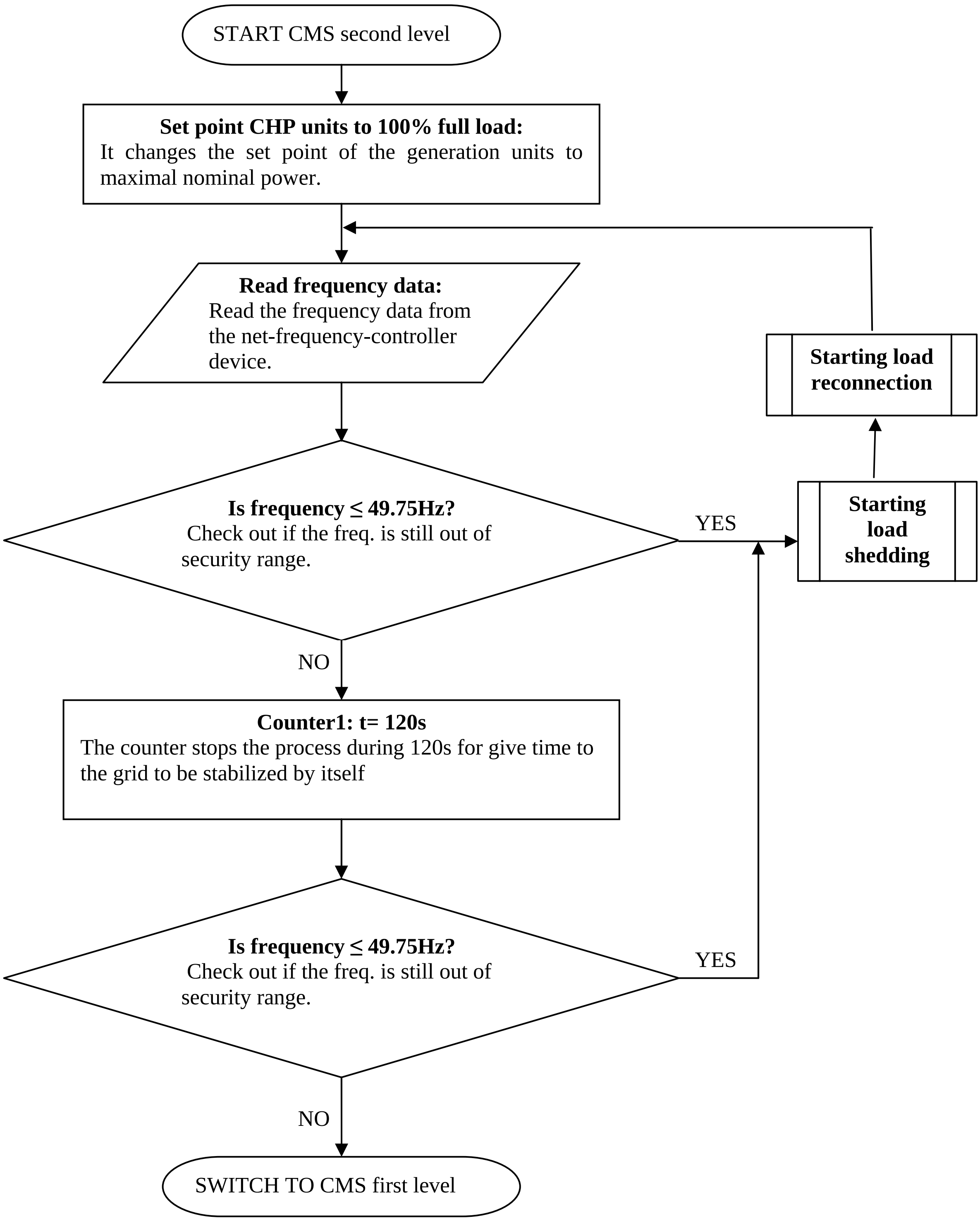


Figure 19: CMS Second Level Flowchart (II)

In the main flowchart there are two subroutines which are the load shedding process and the load reconnection process. These subroutines have been explained before, their flowcharts are given in figure 20 and 21.

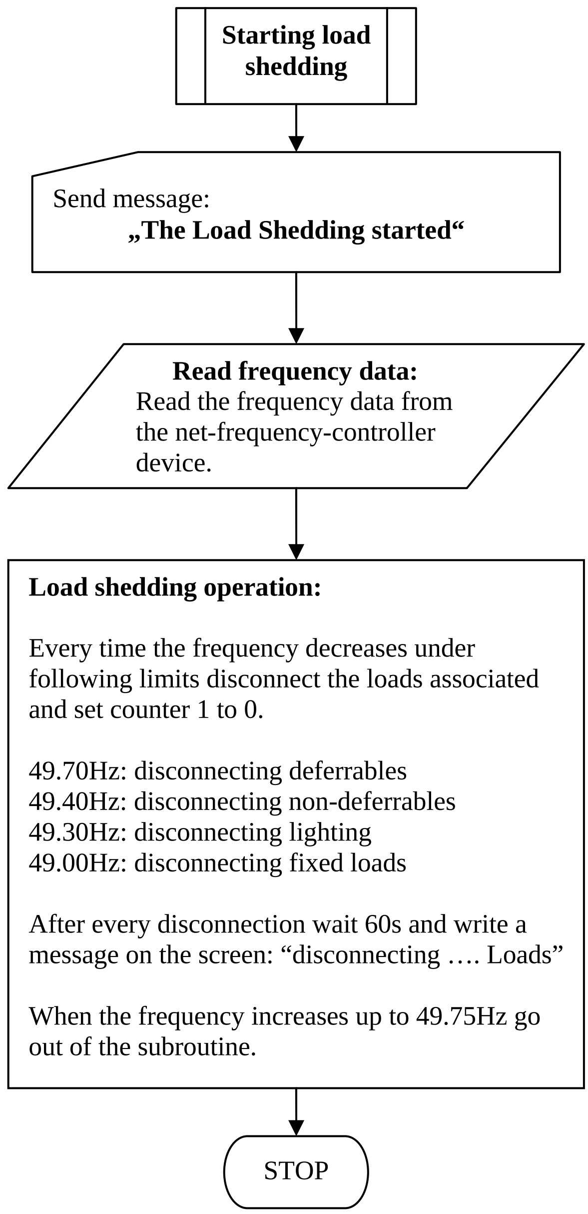


Figure 20: Load shedding subroutine

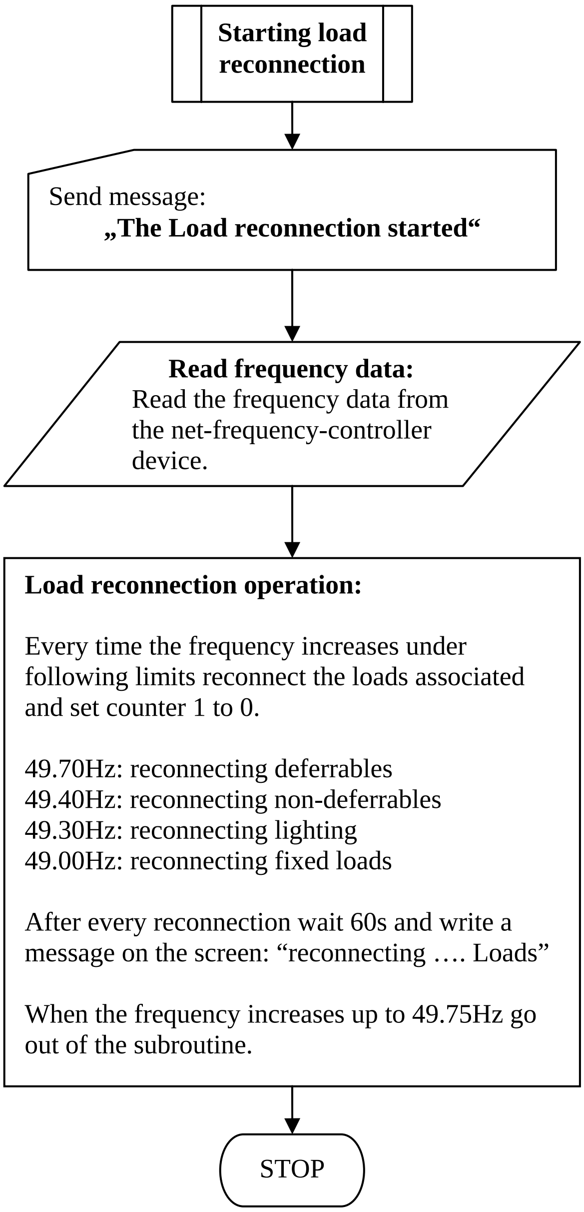


Figure 21: Load reconnection subroutine

5.3 Solving the conflict of interests

The CMS first level is controlled in order to obtain the highest possible economical benefit by using the Energy Market. The CMS second level is controlled for helping the main grid in the frequency stabilisation process. There is obviously a conflict of interests between both the CMS first level and the CMS second level.

The solution proposed to this conflict is a bilateral compromise between both; main grid operator and minigrid operator. To change from CMS level one to CMS level two means to the minigrids owner to subject its economical benefit to the stability of the main grid. Therefore, this compromise must result in a contract between both parts.

By means of this contract, the main grid operator is obligated to reward the minigrid; and the minigrid operator is obligated to subordinate the control of the minigrid to the CMS second level.

The reward for the minigrid and the operation parameters[1] should be defined after a negotiation between both parts.

[1] The operation parameters in this work were product of the assumptions referred earlier.

CHAPTER 6

CMS EMERGENCY LEVEL

The CMS emergency level is activated when the islanding process starts. This can be provoked by a big disturbance in the main grid (tripping the protections of the minigrid), by an unexpected switching process or by a prescheduled switching event.

This emergency level has been considered out of the scope of this thesis, therefore this chapter will only introduce an overview of the stability problems which can provoke the minigrid to split into island mode and the main problems the minigrid faces when it happens.

6.1 Overview of the Stability problems in power grids

The Modern power systems are the result of the interconnections of many different devices every one with a different dynamical response. The behaviour of the whole system can not be simply studied as a set of linear equations but a highly non-linear system. The study of the stability of this system is being the focus of researchers, industries and governmental agencies. The importance of this phenomenon is easily revealed since it has been the seed of many major blackouts [57].

One of the latest studies performed as an effort for classifying the power system stability [58] reveals three main categories of stability: Rotor angle stability, voltage stability and frequency stability. See on figure 22.

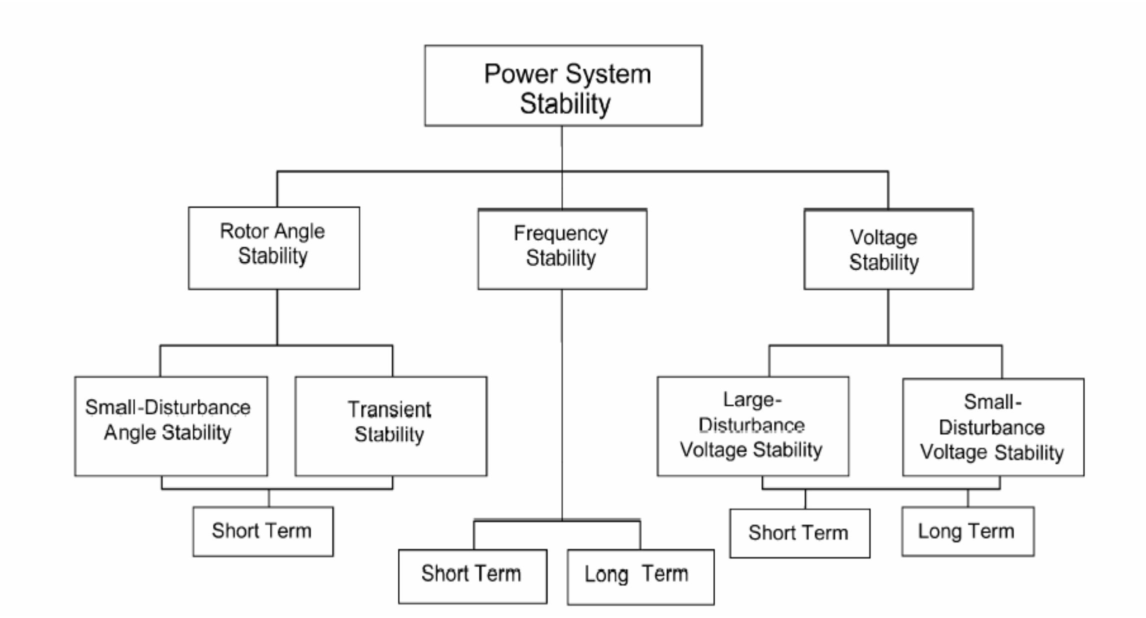


Figure 22: Power system stability classification
(*Source: Prabha Kundur's power stability classification*)

6.1.1 Rotor angle stability

The rotor angle stability is the capability of synchronous generators to remain in synchronism after a disturbance. This instability is related to the ability of the own generator to maintain the equilibrium between the electromagnetic and the mechanical torque.

Standard generator excitation controllers are helpful in achieving rotor angle stability or voltage regulation. The problem can appear when a severe fault occurs close to the generator terminal. Afterwards, simultaneous transient stability or voltage regulation may be difficult to achieve [59]. The solution that researchers in this field are proposing is the use of flexible AC transmission system controllers (FACTS) [60].

6.1.2 Voltage stability

Voltage stability is the ability of a power system to maintain steady voltage in the different lines after a disturbance.

After an increase in the load of the system, the generators increase their power output to restore the steady state of the system. Increasing this output (Intensity flow) means increasing the reactive power due to the inductance of the power lines. The result of this is the decrease of the voltage at the load. As follows a small one single phase example is used for showing this phenomenon, see on figure 23.

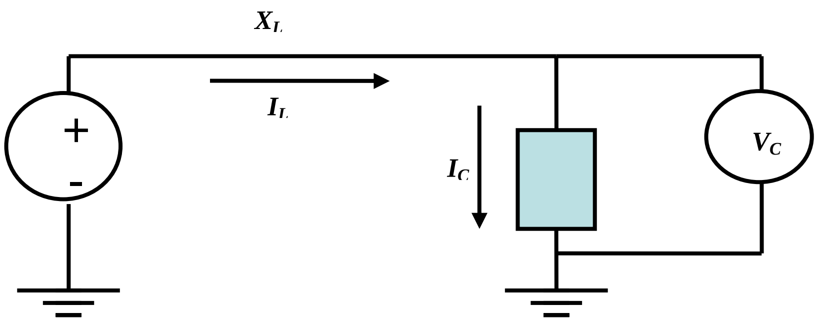
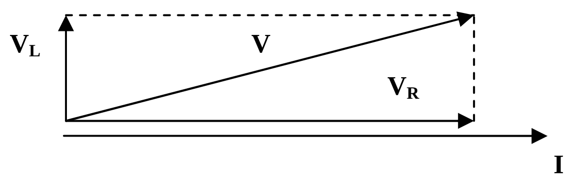


Figure 23: Single phase circuit

When the intensity of the system I (I= I_L=I_C) experiences a sudden increase, the reactive voltage due to the transmission line X_L also increases:

$$V_{transmission\_line} = V_L = I \cdot X_L$$

This results in a decrease of the V_R while the V (output of the generator) assumes this increase in the reactive power.



Depending on the reaction speed of the system the voltage V_R will experience a decrease and after an increase. This phenomenon is called the voltage instability.

The voltage stability becomes a main problem when the reactive power increases beyond the capacity of the reactive power generation devices of the system. Then, the system becomes instable.

Different methods have been defined for evaluating the voltage stability such as using modal analysis [61] or those using static and dynamic approaches [62].

6.1.3 Frequency stability

Frequency stability is the ability of a power system to maintain steady frequency after a sudden imbalance between load and generation. This imbalance is result of many parameters like control delays or the inertia of the generators.

In a strongly interconnected power system the change experienced in system frequency subsequent to a large loss of load or generation is normally less than 2%. However after a severe upset the power system frequency can experience derivations as large as 3-5% [63].

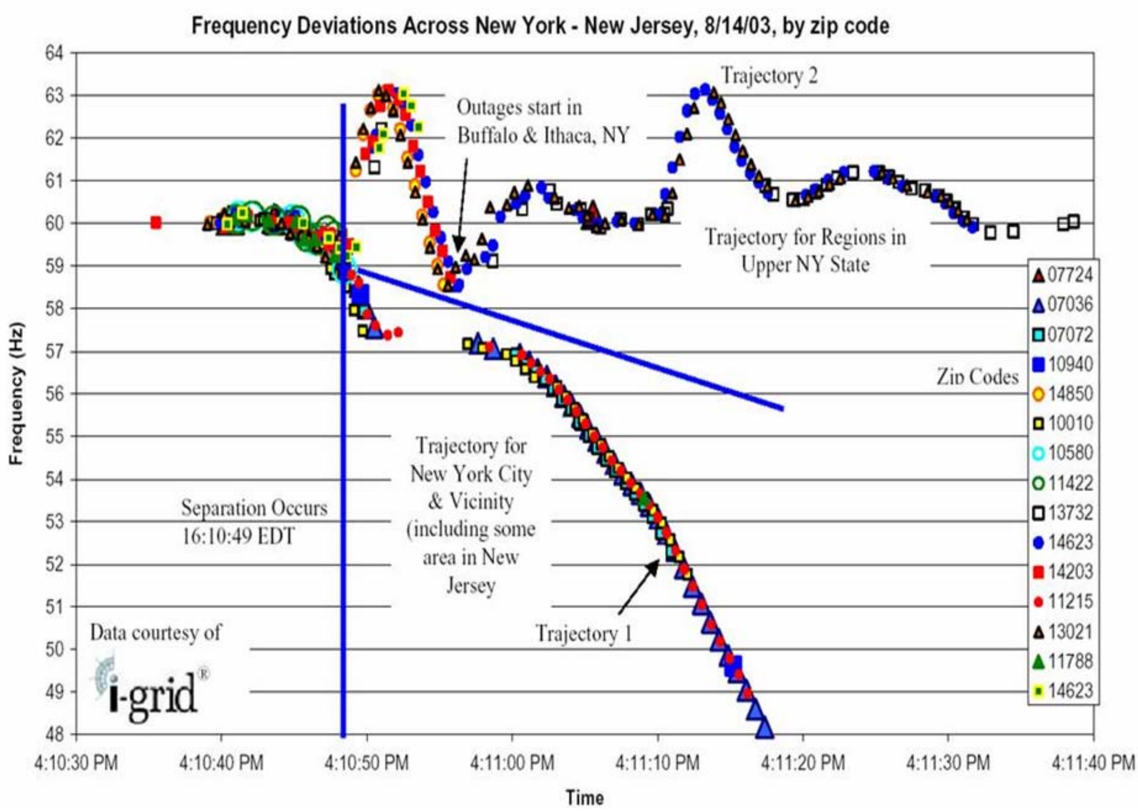


Figure 24: Frequency deviations leading to a blackout *(Source: PNL)*

This instability can result in a fluctuation of the system frequency causing the tripping of the system protections. Moreover, it can drive to the disconnection cascade process that leads to a blackout; an example of it is the New York – New Jersey blackout on 8/14/2003, see on figure 24 [64].

6.2 Minigrid Instability Main Indicators

The obvious difference between large power systems and minigrids is the size. This difference in the size makes minigrid's inertia lower than large power systems; and consequently it makes minigrid more vulnerable to any kind of upsets.

The monitoring of the stability of a minigrid will be related to two main parameters: frequency and voltage. These two parameters act as indicators of the frequency stability and voltage stability of the minigrid. The third kind of instability, rotor angle instability, is more related to the control system of the generator than the monitoring system of the minigrid. Because of that, it has not been considered matter of this study.

6.2.1 Frequency

The frequency is an indicator of the balance between load and generation in the power system. A sudden increase in the load is shown as a decrease in the system frequency, the recuperation time to the steady frequency and the swing level indicates the stability of the system to frequency changes.

An example of the reaction of a minigrid working in islanding conditions to the disconnection of a 70kW active load, followed by its reconnection 1 second later is shown in figure 25. This study was carried on under the Minigrids Simulation Plataform in the Minigrids Project [65].

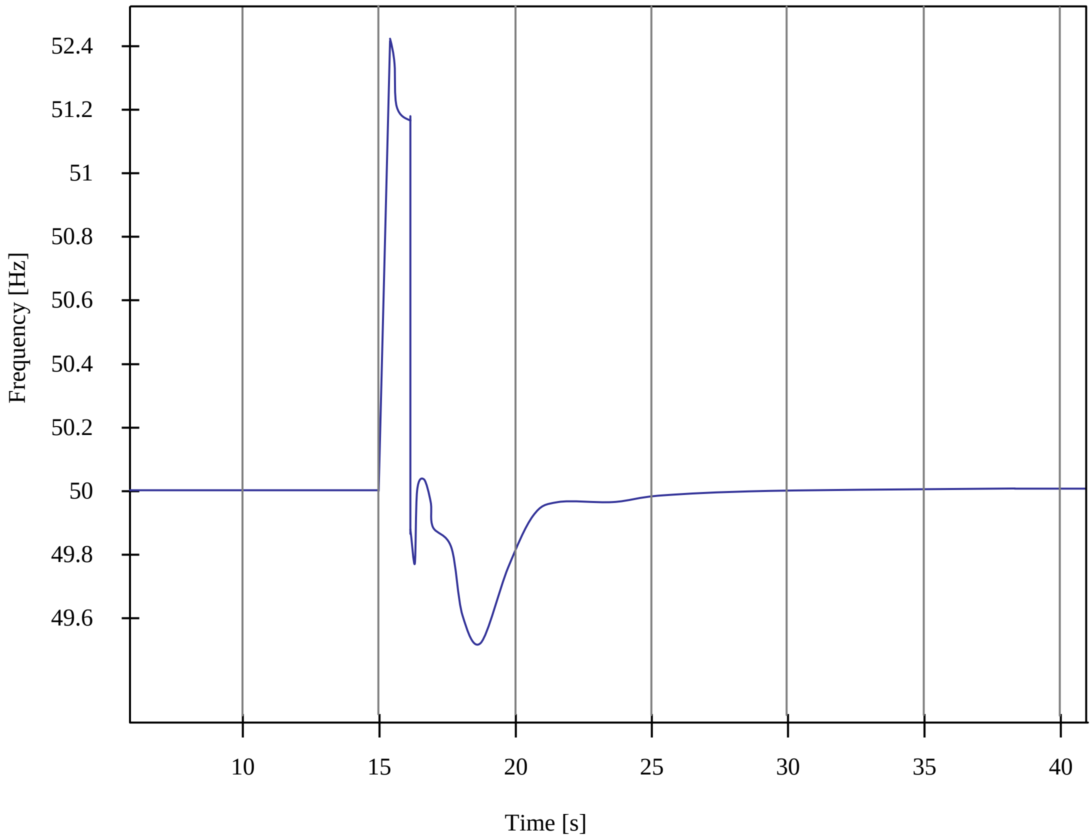


Figure 25: Frequency Deviations disconnecting and reconnecting a 70kW load to a microgrid *(Source: MicroGrids project)*

The frequency in our minigrid will be monitored in the feeder from the main grid, where the protection devices are located and in the bus of the generation resources to the consumer loads.

6.2.2 Voltage

The voltage as said in point 6.1 is the indicator of the reactive power in the system. After an increase in the load of the system, the distributed generation resources must be able to compensate the increase of reactive power. If this is not possible the result is a drop in the voltage level of the loads.

In order to identify when the reactive power reaches the limit of the generation resources a voltage measurement device must be installed in the loads feeder. This device will send an emergency signal to the centre control.

6.3 Analysis Scenarios

The analysis of the stability in a minigrid depends on whether it is working connected to the main grid or it is working in island. Therefore, the stability study has been carried on independently for the three scenarios.

The first scenario would describe the situation when the minigrid is working exchanging electricity with the main grid. In the second scenario, the minigrid is isolated, working as an energy island. The third scenario presents the transition period between scenario one and scenario two.

6.3.1 Minigrid connected to the main grid

While the minigrid remains connected to the main grid, the stability of the minigrid by itself is not an issue. Therefore, the emergency mode is not connected.

6.3.2 Minigrid splits into island mode

Islanding process of a minigrid can be provoked by a big disturbance in the main grid, by a unexpected switching process or by a prescheduled switching event. The big disturbance in the main grid would be responsible of the tripping of the protections of the feeder input to the minigrid.

When the islanding process is scheduled, the transients resulting are minimal and the minigrid can continues operation [66].

When the islanding process is not planned the severity of the transient experienced in the minigrid is highly dependent on [67]:

- pre-islanding operation conditions
- type and allocation of the fault that initiates the islanding process
- islanding detection time interval
- post-fault switching actions that are envisioned for the system
- type of DG units

Latest work being done in this field indicates that it is possible a seamless and rapid connection and disconnection with the main grid, using inverters [68]. The critical system performances are the voltage versus reactive power drop and power versus frequency drop [69]. When voltage control detects an increase in the reactive power the reaction must be an increase in the voltage output of the generation source and vice versa. When the minigrid separates from the main grid, the voltage phase angles at each microsource in the minigrid change, resulting in an apparent reduction in local frequency. This frequency reduction indicates to the controller of every DER that the power output must increase.

6.3.3 Minigrid working in island

Standard configuration of minigrid control system for allowing the minigrid working in island, are formed by three main components:

- Grid forming unit: This unit controls minigrid voltage and frequency. Standard systems content only one of these units, called master.

- Grid supporting unit: These units active and reactive power are determined by the grid forming unit.

- Grid parallel unit: These units comprise loads and uncontrollable generators.

Early configurations of minigrids were based on the structure master-slave, one master grid forming unit and the rest slave units. In the case presented in this work, the master unit is the CHP controller. It sets the frequency and voltage parameters of the minigrid.

Latest work in this field proposes the use of another configuration: multi-master configuration [70]. The advantage of this method is to avoid the control bus system. The supervisory control provides the parameters settings for each component and the different controllers adjust their work by using the own grid voltage and frequency as indicators. This new control idea has been successfully implemented in the development of inverters, such as Sunny Boy, in the case of PV inverters, or Sunny Island, in batteries inverters [71].

CHAPTER 7

TESTING THE PILOT PLANT

This chapter describes the simulations performed and the experiment carried out in the DeMoTeC laboratory at the Institut für Solare Energieversorgungstechnik (ISET) in Germany. The objective of the experiment is to set-up of a pilot plant based on this thesis idea and to test this configuration in a real case for small disturbances.

The laboratory test plant is described as follows:

7.1 Laboratory Test plant

The test plant was built up at the DeMoTeC laboratory. The idea of the experiment is to represent the case of a small disturbance in the Mallorca power grid and evaluate the impact of the studied minigrid with the proposed CMS in the frequency stabilization process.

In order to adapt the studied case to the real plant some simplifications and changes have been proposed. These simplifications are presented in the points below.

The data used in the experiment, for example, energy demand of the minigrid or sudden increase in the power demand of the main grid, as well as energy prices, photovoltaic production, thermal demand, etc are real data measured on 17th February 2004. This day was chosen due to a high increase in the power demand of the main grid and a high power demand of the minigrid, see on chapter 2.

An example of the daily and monthly evolution of the demand on the main grid can be seen in figure 26. It can be noted that the peak demand is given in the summer time and the lower in the winter time.

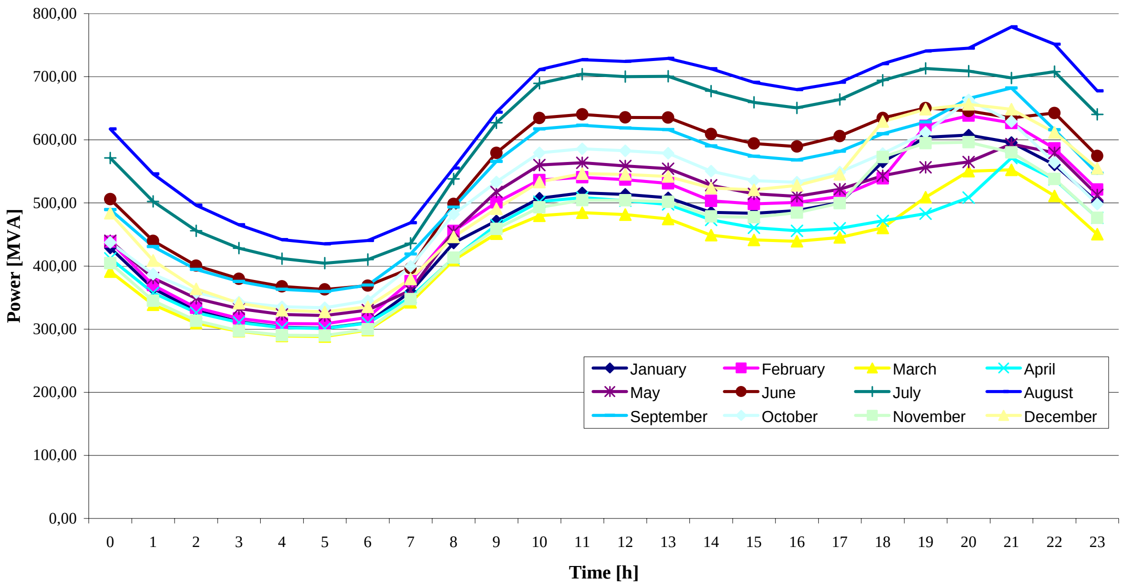


Figure 26: Balearic Islands daily average demand profile. 2001 *(Source: ENDESA)*

The increase from year to year in the demand is in the summer months slightly higher than in winter months, although these are average results.

The 17th February of 2004 was a especially cold day, which means that the increase of the power was higher than the normal. At 10:00 in the morning the power demand was 424MVA and suddenly the demand increased to 464MVA (ΔP=40MVA – 9% disturbance). This grid configuration is the one represented in this experiment.

7.1.1 Equivalent laboratory test - real case

The experiment started running the CMS first level in order to set the starting point of the minigrid. When the system is stable a sudden increase in the power demand of the main grid provokes an imbalance between demand and production. This step is of 40MVA in the main grid of Mallorca, if we use per-units system the step value would be 0.29puMVA. The base power value is 140MVA.

On chapter 2, the different loads in the minigrid were classified. The calculated values at 9:00 on 17th February 2004 were:

Deferrable load	-> 560 kVA (0.004puMVA)
non-deferrable due activity	-> 1213kVA (0.0086puMVA)
Lighting	-> 523kVA (0.0037puMVA)
Fixed load	-> 37kVA (0.00026puMVA)

The set point of the generation units is determined by running the CMS first level software, see point 7.2.

7.1.2 Grid simulator

The grid in this experiment was simulated with a DC machine coupled with a synchronous generator, see on figure 7.2. The set up of the grid simulator is explained in Annex III.

The first simplification proposed in the experiment was the grid selection. The grid selected was the IEEE 14 Node Test Case power grid. This grid represented the Mallorca power grid. The reason of this simplification was the lack of real data of the node characteristics of the Mallorca power grid.

Figure 27: Grid Simulator at DeMoTec laboratory

The step of power in the system should be of 0.29puMVA. The three controllable resistive loads used for simulating this step are of 36kW. There was no availability of generation units in the laboratory at the moment of this experiment, therefore the reaction of the CHP could not be contemplated. In order to see how the load shedding would help, the CHP reaction capacity was added to the power step, the result was a power step of 0.27puMVA. The base power used in the laboratory experiment was 140kVA.

7.1.3 Laboratory Minigrid

The second simplification proposed was the loads in the minigrid. The real minigrid was composed by a set of CHP units and four kind of loads. The minigrid tested in the laboratory was composed by 3 different kinds of loads: deferrables, non-deferrables and lighting, the fixed load was not contemplated due to its small size. There are no generation units, the experiment runs only with steps of loads.

The amount of power per step is:

- Deferrable loads – 600W (0.004pukVA)
- Non-deferrable – 1500W (0.010pukVA)
- Lighting – 510W (0.0036pukVA)

The base power used in this case is 140kVA.

The different loads in the experiment were represented by groups of lights in order to see when a load was disconnected and reconnected, see figure 28.

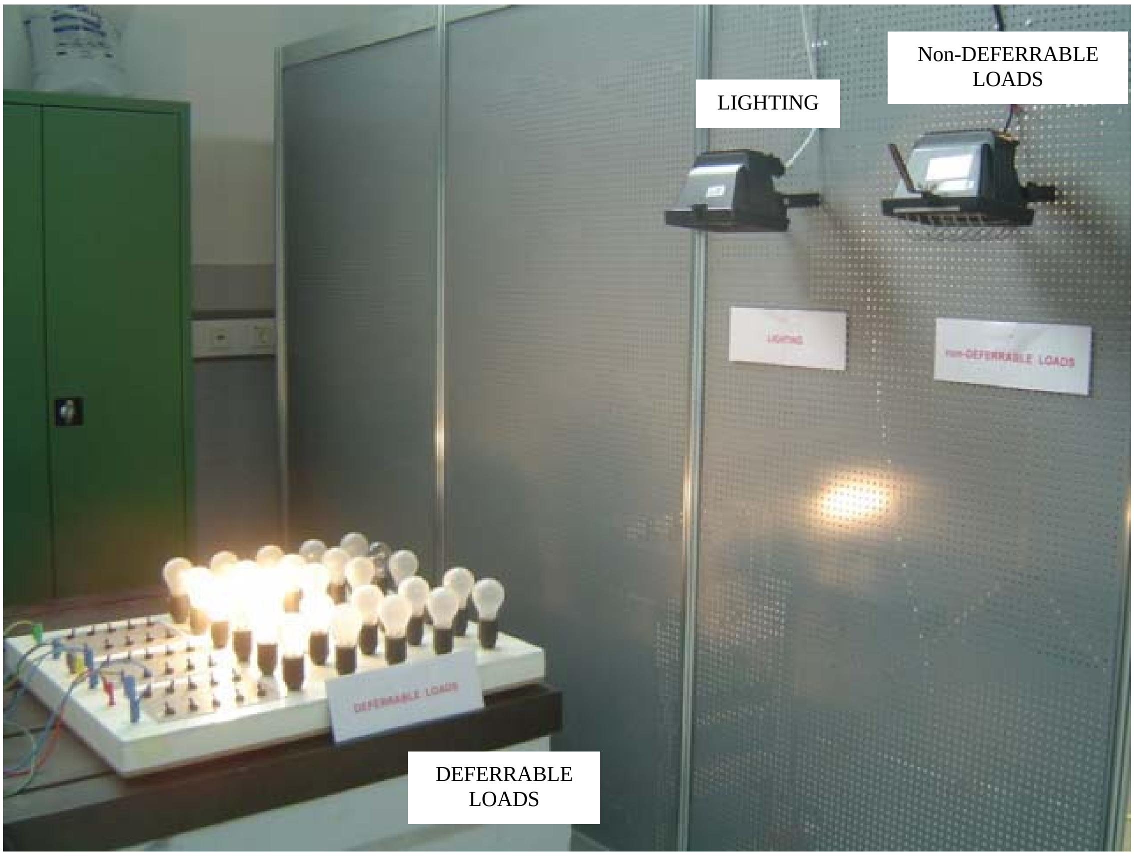


Figure 28: Minigrid Load simulation

These different loads are connected to three different groups of relays and these relays controlled by a Net-Master controller. The Net-Master permanently monitors the frequency in the system and writes the information in a SQL database. The Net-Master reads the orders in the database. The CMS software reads this data and writes the orders for the Net-Master operation in the SQL data basis.

7.2 CMS first level

The CMS first level is used in order to set the starting point of the generation units. To run the first level software the excel table with the different known variables must be created, see on table 11.

TABLE 11: Known variables[1] in the CMS first level

A	B	Pf	Pe	Pu	Pv	C	T	E	F	H
1242	1460	0,203	0,0240	0,0630	0,0918	0	0,0000	0,00	932,5712	30,4
1242	1460	0,203	0,0211	0,0359	0,0647	0	0,0000	0,00	932,5712	121,6
1242	1460	0,203	0,0219	0,0359	0,0647	0	0,0000	0,00	932,5712	30,4
1242	1460	0,203	0,0186	0,0359	0,0647	0	0,0000	0,00	932,5712	91,2
1242	1460	0,203	0,0186	0,0359	0,0647	0	0,0000	0,00	932,5712	30,4
1242	1460	0,203	0,0178	0,0359	0,0647	0	0,0000	0,00	932,5712	121,6
1242	1460	0,203	0,0185	0,0359	0,0647	0	0,0000	0,00	932,5712	60,8
1242	1460	0,203	0,0201	0,0359	0,0647	0	0,0000	0,00	932,5712	2508,0
1242	1460	0,203	0,0239	0,0359	0,0647	0	2683,3333	0,00	3495,2847	1120,4
1242	1460	0,203	0,0240	0,0630	0,0918	0	2744,6465	6,02	1001,5737	135,8
1242	1460	0,203	0,0244	0,0630	0,0918	0	2440,8081	6,02	1001,5737	560,0
1242	1460	0,203	0,0270	0,0630	0,0918	0	2042,0202	6,02	1001,5737	526,8
1242	1460	0,203	0,0270	0,0630	0,0918	0	1633,4343	6,02	1001,5737	944,7
1242	1460	0,203	0,0256	0,0630	0,0918	0	1546,9697	6,02	884,7064	955,0
1242	1460	0,203	0,0250	0,0630	0,0918	0	1399,1919	6,02	877,3112	75,0
1242	1460	0,203	0,0223	0,0630	0,0918	0	1351,3131	6,02	994,1785	0,0
1242	1460	0,203	0,0219	0,0630	0,0918	0	1343,4343	6,02	1056,8337	1040,9
1242	1460	0,203	0,0201	0,0630	0,0918	0	1134,0404	0,00	1056,8337	684,0
1242	1460	0,203	0,0219	0,1071	0,1359	0	1593,8384	0,00	2114,6322	1167,5
1242	1460	0,203	0,0224	0,1071	0,1359	0	2034,9495	0,00	1873,2334	916,7
1242	1460	0,203	0,0304	0,1071	0,1359	0	0,0000	0,00	1873,2334	500,0
1242	1460	0,203	0,0282	0,1071	0,1359	0	0,0000	0,00	932,5712	60,8
1242	1460	0,203	0,0250	0,0630	0,0918	0	0,0000	0,00	932,5712	0,0
1242	1460	0,203	0,0211	0,0630	0,0918	0	0,0000	0,00	932,5712	121,6

7.2.1 Results of the CMS first level

The result of the use of the CMS first level software is given in two different tables the first one 12 is the electrical balance and 13 is the thermal balance of the minigrid.

[1] The known variables have been calculated in chapter 2.

TABLE 12: CMS first level: Electricity balance result

TIME	Load		Electricity								
	Motor 1	Motor 2	Electricity Production	Total Demand of the costumer	Surplus to the main grid	price for the costumer	price of the energy market	price for the main grid	Benefit from selling to the costumer	Benefit from selling to the main grid	Cost of buying in the energy market
	%	%	MWh_e	kWh_e	kWh_e	€/kWh_e	€/kWh_e	€/kWh_e	€	€	€
00:00	100,00%	100,00%	2,92	962,97	1957,03	0,0630	0,0240	0,0528	60,65	103,39	0,00
01:00	100,00%	100,00%	2,92	1054,17	1865,83	0,0359	0,0211	0,0500	37,85	93,23	0,00
02:00	100,00%	100,00%	2,92	962,97	1957,03	0,0359	0,0219	0,0507	34,57	99,30	0,00
03:00	0,00%	0,00%	0,00	1023,77	-1023,77	0,0359	0,0186	0,0474	36,76	0,00	-19,00
04:00	0,00%	0,00%	0,00	962,97	-962,97	0,0359	0,0186	0,0474	34,57	0,00	-17,87
05:00	0,00%	0,00%	0,00	1054,17	-1054,17	0,0359	0,0178	0,0466	37,85	0,00	-18,73
06:00	0,00%	0,00%	0,00	993,37	-993,37	0,0359	0,0185	0,0473	35,66	0,00	-18,40
07:00	75,00%	0,00%	1,10	3440,57	-2345,57	0,0359	0,0201	0,0489	123,52	0,00	-47,03
08:00	75,00%	100,00%	2,56	4615,68	-2060,68	0,0359	0,0239	0,0527	165,71	0,00	-49,19
09:00	100,00%	100,00%	2,92	1137,37	1782,63	0,0630	0,0240	0,0528	71,64	94,17	0,00
10:00	0,00%	0,00%	0,00	1534,57	-1534,57	0,0630	0,0244	0,0532	96,66	0,00	-37,40
11:00	100,00%	100,00%	2,92	1528,37	1391,63	0,0630	0,0270	0,0559	96,27	77,73	0,00
12:00	0,00%	0,00%	0,00	1946,27	-1946,27	0,0630	0,0270	0,0558	122,59	0,00	-52,55
13:00	0,00%	0,00%	0,00	1839,71	-1839,71	0,0630	0,0256	0,0544	115,88	0,00	-47,04
14:00	100,00%	100,00%	2,92	952,31	1967,69	0,0630	0,0250	0,0538	59,98	105,94	0,00
15:00	100,00%	100,00%	2,92	994,18	1925,82	0,0630	0,0223	0,0512	62,62	98,54	0,00
16:00	0,00%	0,00%	0,00	2097,73	-2097,73	0,0630	0,0219	0,0507	132,13	0,00	-45,98
17:00	0,00%	0,00%	0,00	1740,83	-1740,83	0,0630	0,0201	0,0489	109,65	0,00	-35,03
18:00	60,00%	0,00%	0,88	3282,13	-2406,13	0,1071	0,0219	0,0507	351,44	0,00	-52,74
19:00	60,00%	0,00%	0,88	2789,93	-1913,93	0,1071	0,0224	0,0512	298,74	0,00	-42,81
20:00	0,00%	0,00%	0,00	2373,23	-2373,23	0,1071	0,0304	0,0592	254,12	0,00	-72,03
21:00	0,00%	0,00%	0,00	993,37	-993,37	0,1071	0,0282	0,0570	106,37	0,00	-27,98
22:00	0,00%	0,00%	0,00	932,57	-932,57	0,0630	0,0250	0,0538	58,74	0,00	-23,32
23:00	0,00%	0,00%	0,00	1054,17	-1054,17	0,0630	0,0211	0,0500	66,40	0,00	-22,29
Total			25,84						2570,34	672,31	-629,39

TABLE 13: CMS first level results: Thermal Balance

TIME	Thermal Energy				
	Thermal Energy Production	Loses in the thermal distribution (17%)	Total Thermal Energy Supplied	Price	Benefit of selling thermal energy
	kWh_{th}	kWh_{th}	kWh_{th}	€/kWh_{th}	€
00:00	2484,00	422,28	2061,72	0,06	123,7032
01:00	2484,00	422,28	2061,72	0,06	123,7032
02:00	2484,00	422,28	2061,72	0,06	123,7032
03:00	0,00	0,00	0,00	0,06	0
04:00	0,00	0,00	0,00	0,06	0
05:00	0,00	0,00	0,00	0,06	0
06:00	0,00	0,00	0,00	0,06	0
07:00	931,50	158,36	773,15	0,06	46,3887
08:00	2173,50	369,50	1804,01	0,06	108,2403
09:00	2484,00	422,28	2061,72	0,06	123,7032
10:00	0,00	0,00	0,00	0,06	0
11:00	2484,00	422,28	2061,72	0,06	123,7032
12:00	0,00	0,00	0,00	0,06	0
13:00	0,00	0,00	0,00	0,06	0
14:00	2484,00	422,28	2061,72	0,06	123,7032
15:00	2484,00	422,28	2061,72	0,06	123,7032
16:00	0,00	0,00	0,00	0,06	0
17:00	0,00	0,00	0,00	0,06	0
18:00	745,20	126,68	618,52	0,06	37,11096
19:00	745,20	126,68	618,52	0,06	37,11096
20:00	0,00	0,00	0,00	0,06	0
21:00	0,00	0,00	0,00	0,06	0
22:00	0,00	0,00	0,00	0,06	0
23:00	0,00	0,00	0,00	0,06	0
Total					1094,77332

As seen in the operation of the CMS first level the CHP units are working from 9:00 to 9:59 at 100% and at 10:00 at 0%.

7.2.2 Economical balance of the minigrid

The calculation of the economical profit of the minigrid depends on different factors related as follows:

Benefit of the thermal energy trade:

Benefit of selling thermal energy = 1094€
Total benefit of thermal energy trade: = 1094€

Benefit of the electricity trade:

Benefit of selling electricity to the costumer = 2570€
Benefit of selling overproduction to the main grid = 672€

Cost of buying electricity of the main grid	= 629€
Total benefit of electricity trade:	= 2613€

Fuel consumption of the CHP units:

Consumption	= 6272 ltres
Price of the fuel for February 2004	= 203 €/m^3
Total cost of the fuel:	= 1273€

Grid connexion cost

Contract with the supply company:	= 383€

Other costs related to the operation:

Operation	= 160000€/year[2]
Maintenance	= 0.01314€/kWhe[2]
Insurance	= 13000€/year[2]
Total other cost for 17.February 2004:	= 836.62€

The total economical profit of the minigrid for 17th February 2004 is 1214€.

The real benefit of the minigrid without using the CMS first level and therefore not participating in the energy market but with data of the generators and prices provided by the minigrid operator was 738€. The real benefits for 17th February 2004 of the minigrid operator were 505€. The reason in the price difference is a discount offered by the minigrid operator in the thermal energy sold to the University.

7.2.3 Set point of the CHP for the test plant

The set point of the CHP units at 10:00 of the studied day is 0%; Nevertheless, at 9:59 was 100%. The step in the main grid is produced instantaneously at 10:00, therefore it has been considered an instant reaction of the CHP units, since the generators were ordered to operate before they could reach the scheduled set point.

7.3 CMS second level

After the step of power is provoked, an imbalance in the power fluxes is generated; as consequence of it the frequency decreases down to 49.75Hz and the CMS second level is activated.

As said before the test grid used is the IEEE 14 Bus Test Case. The software platform used in the simulations is the Alternative Transients Program ATP EMTP [72].

[2] Data given by the grid operator

7.3.1 IEEE 14 Bus Test Case

The IEEE 14 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern US) as of February, 1962 [73]. It was selected from other test cases due its simplicity in order to test it in the laboratory. The data of the generators and data of the grid are giving as follows.

This IEEE test case is composed by 5 generators, 14 nodes, resistance and reactive loads and different lines and transformers, see ATP simulation of the grid in figure 29.

The characteristics of the generators used in our simulation are given in table 14. Typical values have been assumed.

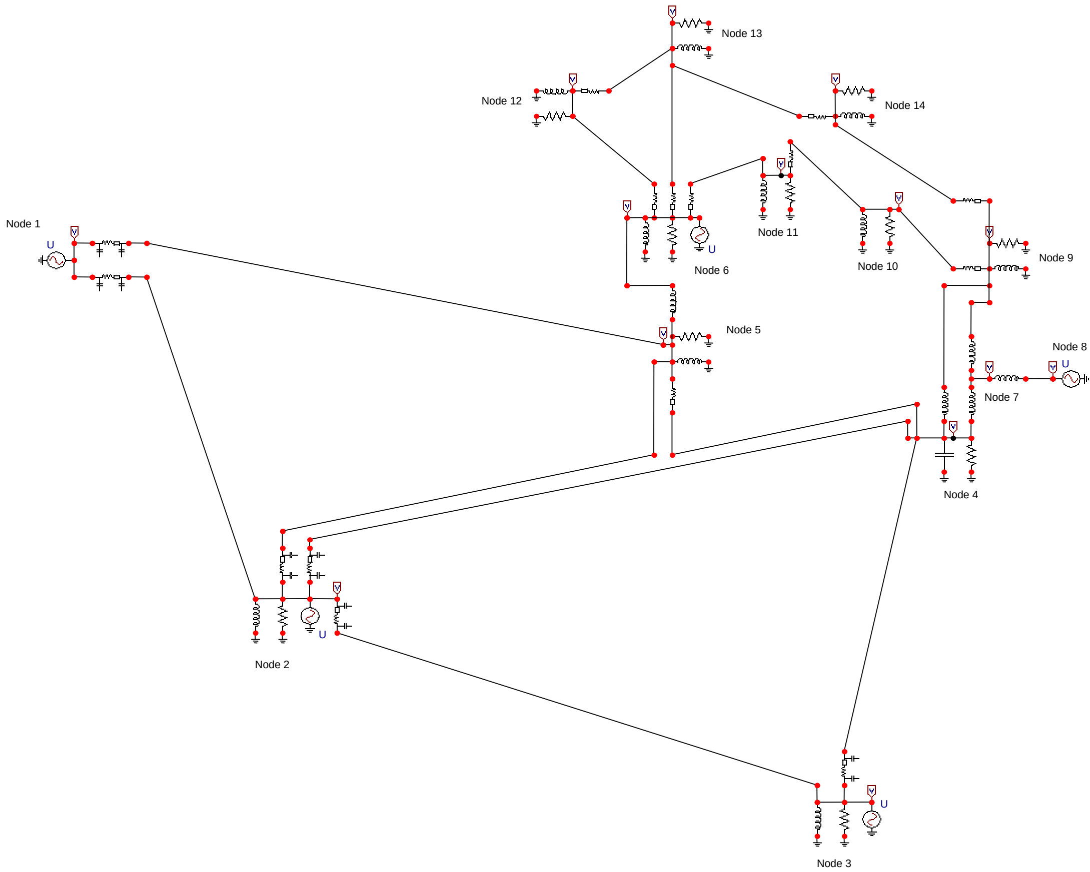


Figure 29: ATP model of the IEEE 14 Nodes Test Case

TABLE 14: Characteristics of the generators

Generator	Type	R [Hz/puMVA]	T_R [s]	T_T [s]	T_{RC} [s]	T_{BP} [s]	α	β	γ
G1	TPS[3]	5	0.1	0.3	-	-	-	-	-
G2	TPS	5	0.1	0.3	-	-	-	-	-
G3	TPS	4	0.1	0.3	-	-	-	-	-
G4	TPS-CC[4]	4	0.1	0.3	10	0.45	0.3	0.3	0.4
G5	TPS-CC	4	0.3	0.35	10	0.45	0.3	0.3	0.4

Being:

R: frequency response constant of the generator

T_R: time constant of the reaction of the primary control of the turbine

T_T: time constant of the mechanical reaction of the turbine

T_{RC}: time constant of the after heater in the combined cycle system

T_{BP}: time constant of the mechanical reaction of the low pressure turbine

α, β, γ: proportion of the contribution to the total power output of the different step

7.3.2 D constant of the grid

The D constant of the system represents the relation between Frequency and Load in the system, D [MW/Hz]. This relation characterizes the response of the system for an operation point. The D constant was determined by changing the frequency parameter in a small range and obtaining the different power consumption of the system, in the ATP simulation carried out.

The result of the simulation at 49.8Hz and at 50Hz is given in table 7.5.

TABLE 15: Operation of the system at different frequencies: Results

	49.8Hz			50Hz		
Node	Vp_pu	VRMS_pu	P_pu	Vp_pu	VRMS_pu	P_pu
2	1,47	1,04	0,22	1,47	1,04	0,22
3	1,42	1,01	0,94	1,42	1,01	0,93
4	1,46	1,03	0,49	1,46	1,03	0,49
5	1,56	1,1	0,09	1,56	1,1	0,09
6	1,51	1,07	0,11	1,51	1,06	0,11
9	1,46	1,03	0,28	1,45	1,03	0,28
10	1,46	1,03	0,09	1,45	1,03	0,09
11	1,58	1,12	0,04	1,58	1,12	0,04
12	1,49	1,05	0,06	1,48	1,05	0,06
13	1,48	1,04	0,13	1,47	1,04	0,13
14	1,44	1,02	0,14	1,44	1,02	0,14
Total Power			2,5829			2,5775

3 TPS (Thermal Power Station)

4 TPS-CC (Thermal Power Station in Combined Cycle)

Calculation of the D parameter:

$$D = \frac{P_{pu}(49.8Hz) - P_{pu}(50Hz)}{49.8Hz - 50Hz} = 0.03\,puMW / Hz$$

The base power of this grid is 100MVA.

This result of the D parameter was accepted since the value of D for a 1GW grid would be around 0.02puMW/Hz and for a 5GW would be 0.01puMW/Hz.

7.3.3 Simulating the experiment

In order to simulate the behaviour of the minigrid coupled to the main grid before starting the experiment, the coupled system was developed as an ATP model, see on figure 7.5.

The object of the simulation performed was to use this model to check the frequency output of the main grid while using the minigrid as support element with the CMS control system defined previously. The simulations have been performed using a step function which provokes an unbalance between the power fluxes in the system. This step function represents a sudden increase in the power demand. This increase has been considered maximal 10% of the nominal power of our system, due to the use of linear models only small perturbations have been taking into account. The most representative results are giving in the next point.

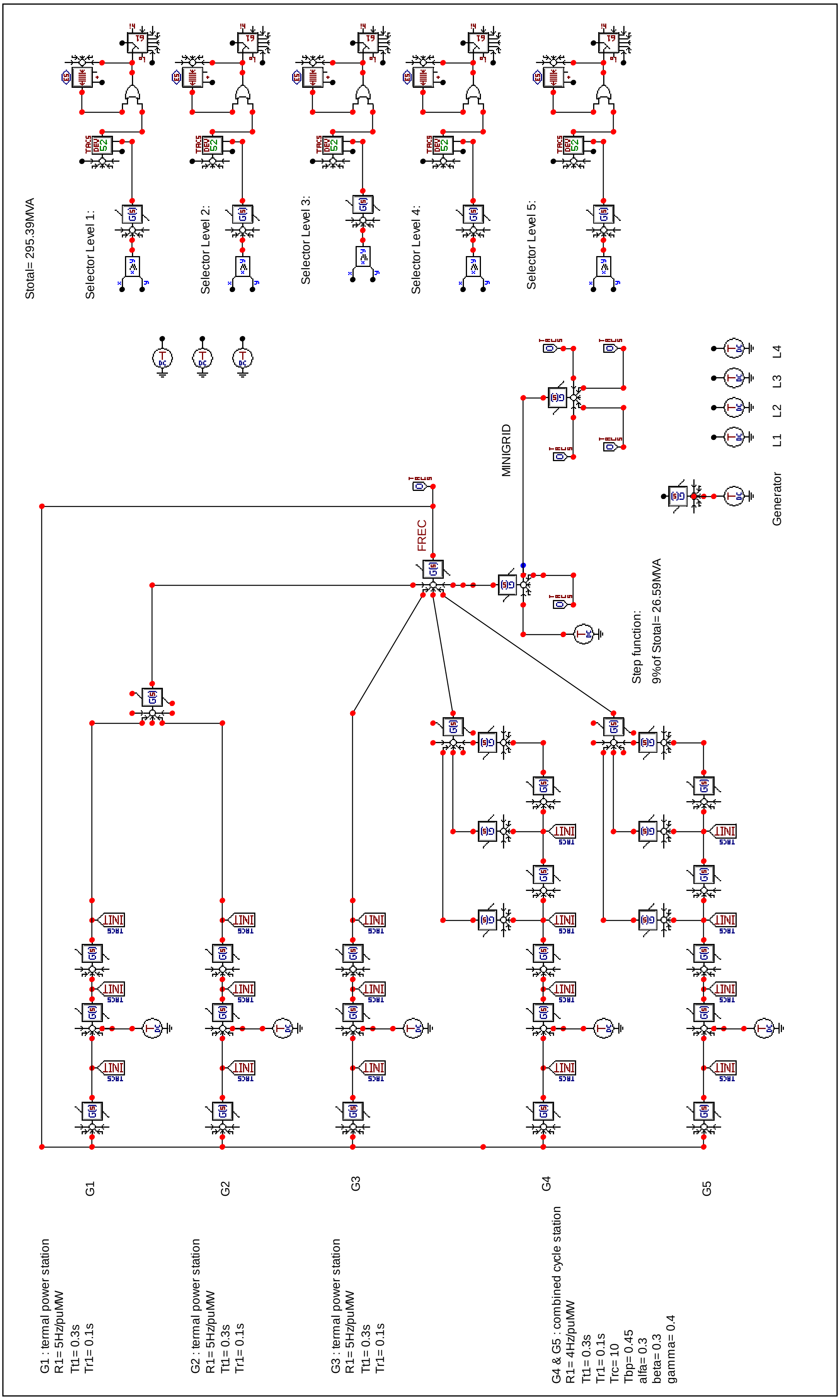


Figure 30: ATP model of the minigrid coupled to the IEEE 14 Nodes Test Case grid

7.3.4 Results of the simulation: Response of the system

The response of the grid was tested for different step functions, in intervals of 2% of the total power (259.39MVA) from 2% to 10%. In order to find the interval where the minigrid could be used a support of the system. Considering the acceptable range of frequency drop from 49.75Hz until 50Hz.

The results for every one of these simulations are given as follows.

Response to a 2% (5.9MVA)

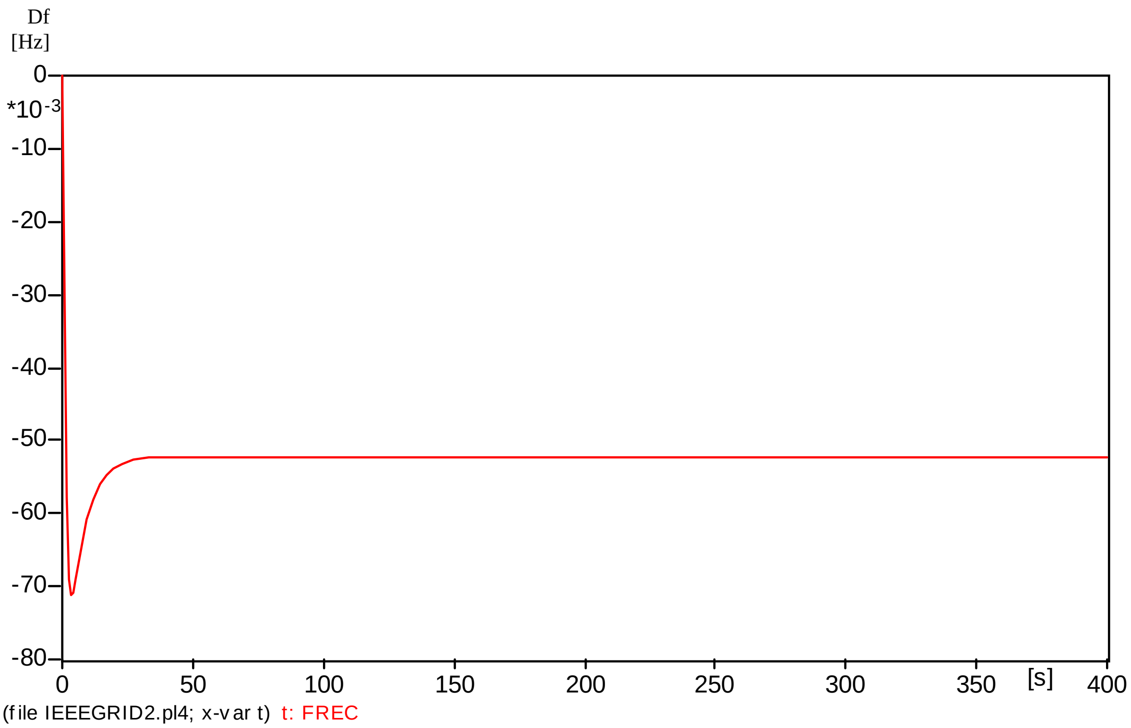


Figure 31: Response of the grid to a 5,9MVA step function

In this case the system finds a new steady state point inside of the security range and the CMS second level would not act, see figure 31.

Response to a 4% (11.8MVA)

In the case of a step function of 4%, meaning a power of 11.8MW, the frequency drop grows in value but still inside the acceptable range. Therefore, the CMS second level remains in stand by, see figure 32.

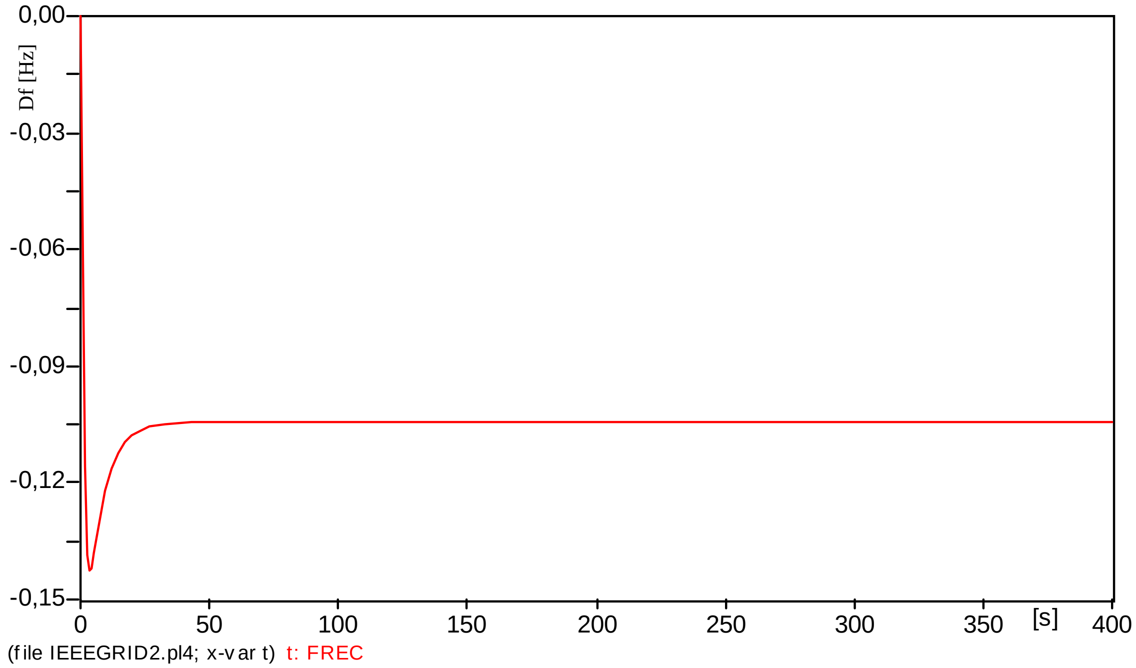


Figure 32: Response of the grid to a 11.8MVA step function

Response to a 6% (17.7MVA)

Increasing the step function is increasing the drop in the frequency of the system but not reaching the point were the frequency is critical, see figure 33. The CMS second level still remains in stand by.

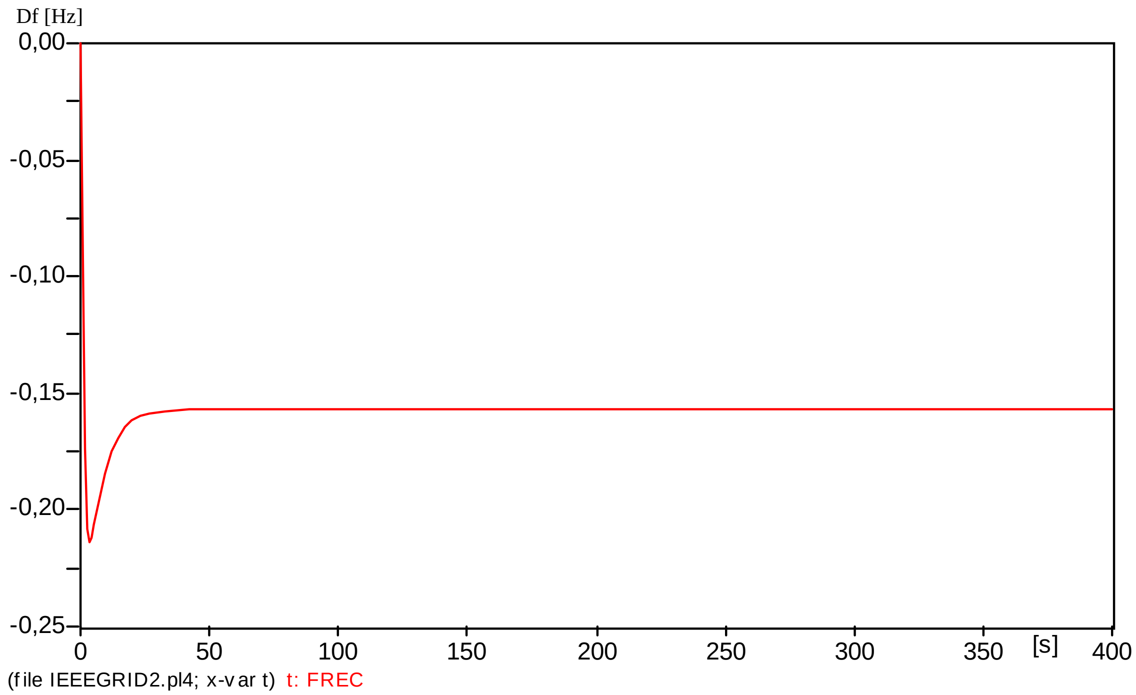


Figure 33: Response of the grid to a 17.7MVA step function

Response to a 8% (26.6MVA)

At this point, the limit of security in the frequency of the system is reached but the system recovers achieving a new steady state point, which is inside the acceptable range, see figure 34.

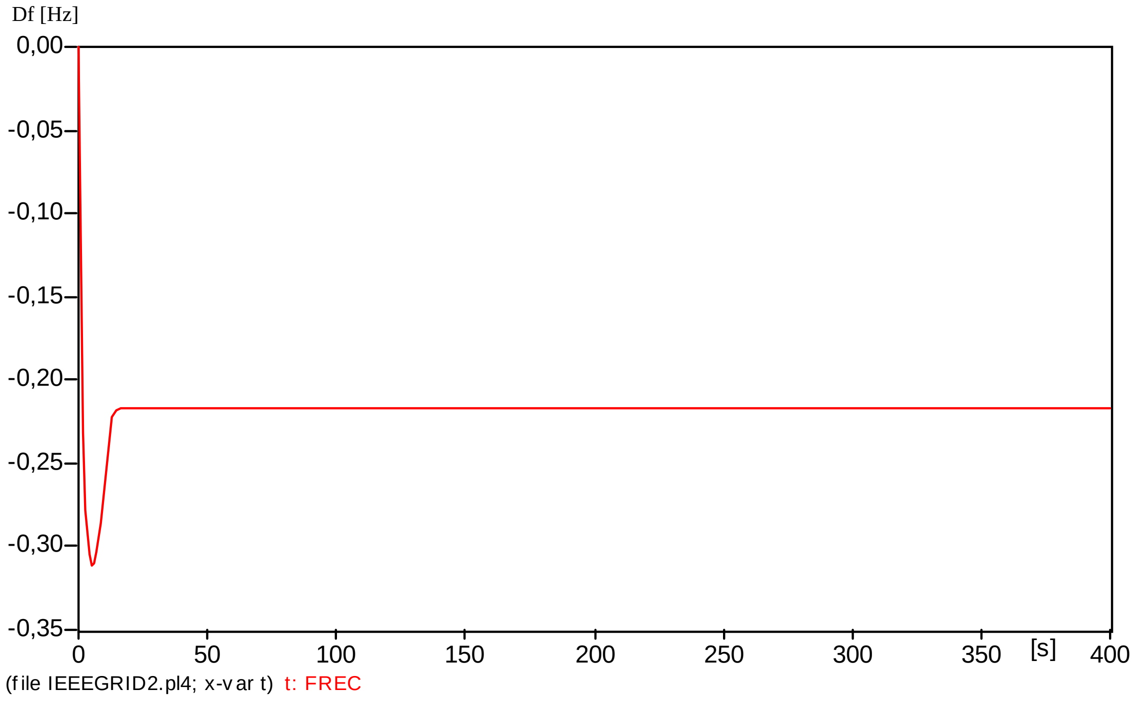


Figure 34: Response of the grid to a 26.6MVA step function

Response to a 10% (29.5MVA)

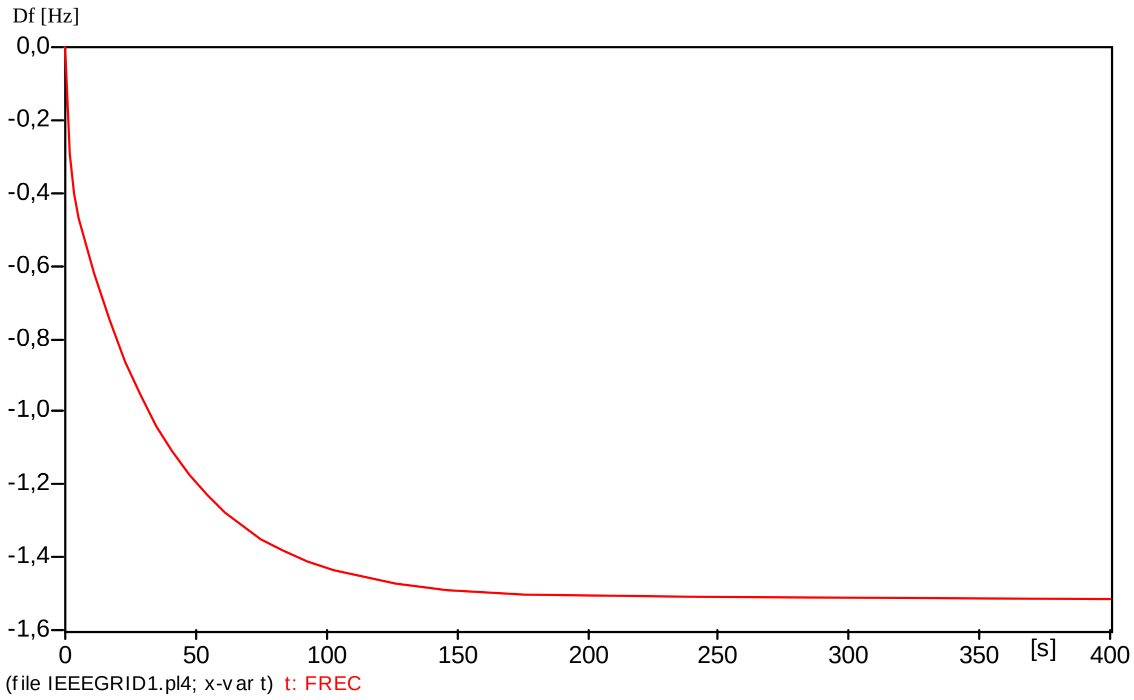


Figure 35: Response of the grid to a 29.5MVA step function

In this simulation the situation of a 29.5MVA step function is presented. With this step power the system is not able to recover by itself and remains out of the acceptable range, see on figure 35. This provokes the reaction of the CMS.

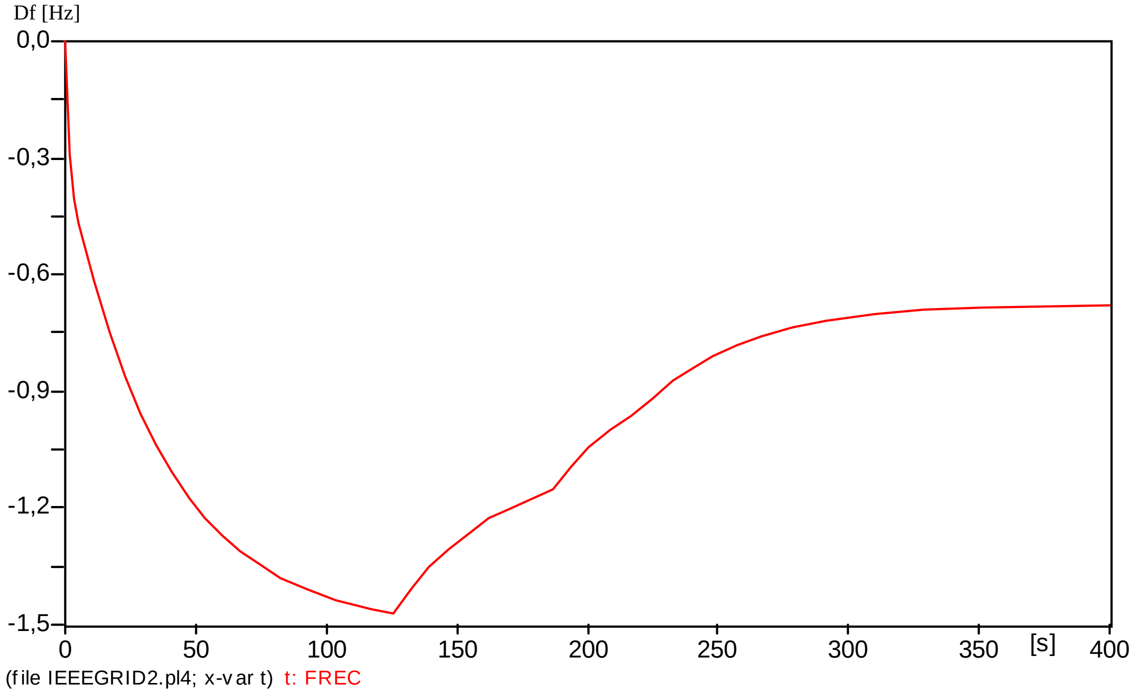


Figure 36: Response of the grid with the CMS to a 29.5MVA step function

The reaction of the CMS increases the frequency of the system but it is not enough for recovering it, see figure 36. Therefore, it can be suggested that the CMS will be useful for the range from 8% to 10%.

Interval from 8% to 10%

Inside this range is the reaction of the minigrid with the CMS second level useful for the system. In order to assess this impact, the following cases will be presented. The experiment performed at DeMoTeC will be based on this feature.

Response to a 9% (26.5MVA)

In this case the system recovers but the steady state frequency remains out of the admissible range. Therefore, the protections in the grid would trip, see figure 37. The purpose of the CMS second level is to avoid this tripping.

Using the CMS second level, a reaction of the microgrid components would avoid the tripping of the main grid protections, see figure 38. The frequency is brought inside the acceptable operation limits.

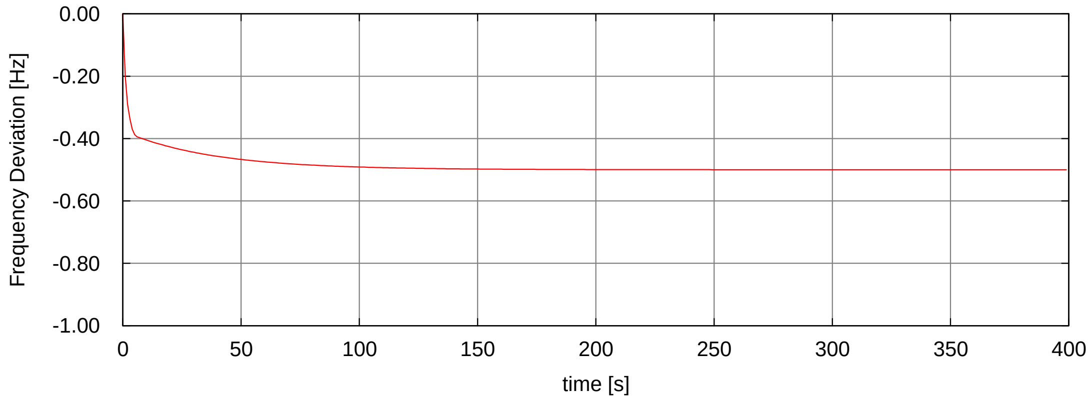


Figure 37: Response of the grid to a 26.5MVA step function

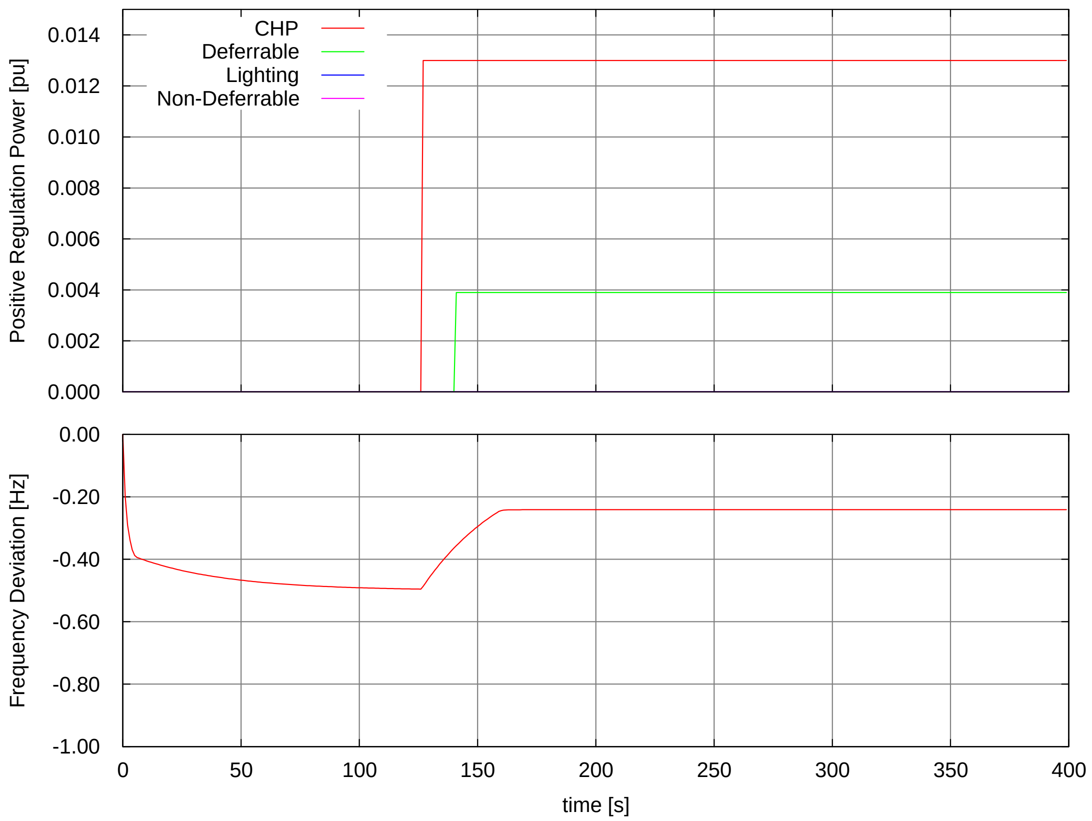


Figure 38: Response of the grid with the CMS to a 26.5MVA step function

The reaction of the CHP units and Deferrable load is also shown.

Response to a 9.5% (28MVA)

The response of the system to a 28MVA is shown in figure 39.

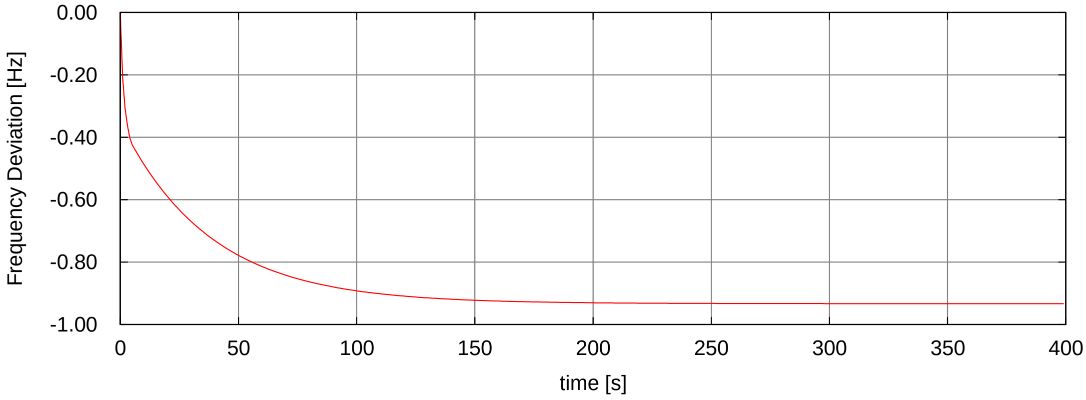


Figure 39: Response of the grid to a 28MVA step function

While using the CMS, the response to a 9.5% step of power provokes the reaction of the different components of the minigrid and the frequency goes up, see figure 40.

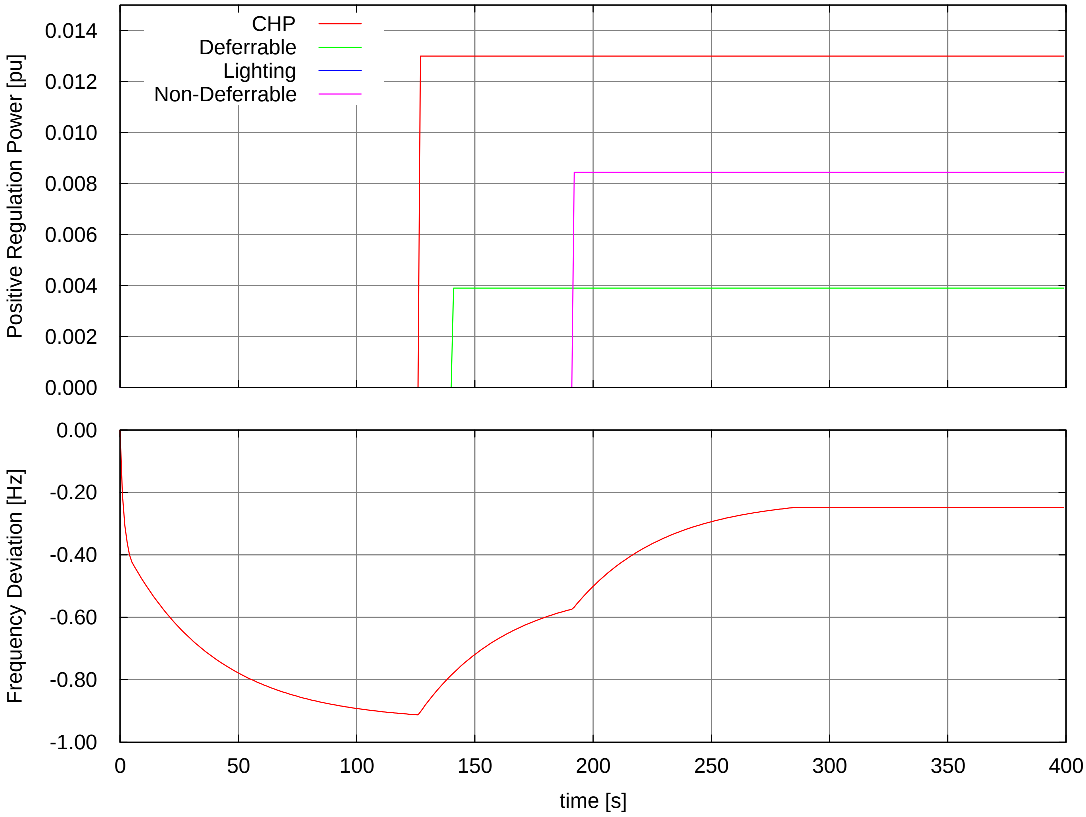


Figure 40: Response of the grid with the CMS to a 28MVA step function

The power step of the different components in the minigrid is also shown.

7.4 Experimental results

Using the data above described the test plant was built up. In this point the procedure followed during the experiment and the final results are given.

7.4.1 Experiment procedure

Before starting the experiment the steps of frequency were set up. The steps of frequency were:

1.- At 49.75Hz – Disconnection of Deferrable loads
2.- At 49.70Hz – Disconnection of non-deferrable loads
3.- At 49.50Hz – Disconnection of Lighting

The procedure followed in the experiment is divided in steps:

<u>Step One:</u>
Start the DC machine control and wait the frequency to be stabilized at 50Hz. The minigrid is full load (all the relays are on). *Typical acceptable oscillations in the reference grid would be in the range between 49.85Hz and 50.15Hz.* Non oscillations in frequency are observed in the experiment.

<u>Step Two:</u>
At this moment we suddenly connect a 36kW resistive load. The result of this connection is an imbalance between power fluxes in the system. The system reacts to this step function with a drop in the frequency. At the begin of the step function a big disturbance in the frequency is observed (from time 0min 0s to time 0min 3s). The reason of that is the P control that the DC machine has already installed.
The frequency drop is registered in the data logger and can be seen from point 0min 3s to point 1min. 55 s, see in figure 7.11.

<u>Step Three:</u>
The frequency drop is detected by the CMS through the Net-master control. When the frequency reaches the 49.75Hz limit (0min 4s), an the following message appears on the PC screen:
"oh, oh, things are going creepy in the Grid, is it really so bad?"
At this point a 100s counter starts.
Second message:
"Holly cow! Got to do something…"
The delay observed in the communication process is 5s, +/- 4s error.

<u>Step Four:</u>
After the 100s the CMS checks the frequency again. It is still lower than 49.75Hz. (time 1min 40s)
The third messages appear on the screen:
"Entering CMS second level. Close your eyes and enjoy…."
At this point the load shedding process begins.
Fourth message:
"Beginning Load Shedding… uy"

Step Five:
The following messages are popping up on the screen while the load shedding process is going on.
First, the deferrable loads are disconnected, time: 1min 55s.
Five message:
"Disconnected Deferrables"
At time 2min 13s the relay of the non-deferrable loads is disconnected.
Six message:
"Disconnected non-Deferrable"
At time 2min 26s the relay of the lighting is disconnected.
Seven message:
"Disconnected Lighting. Oh oh!"
The time delay between the three disconnections is the time the program waits 10s, in order to see if the grid can be stabilized by the disconnection and the communication between the different elements: CMS software, SQL data base and Net-Master Controller.

7.4.2 Results of the experiment

The results of the experiment are given in figure 41. The measurements were done by using a Data logger in the minigrid bus. Therefore the power is only related to the minigrid. The step of power is not presented in the figure, the data logging started when the step was provoked, therefore the oscillations on the frequency can be seen.

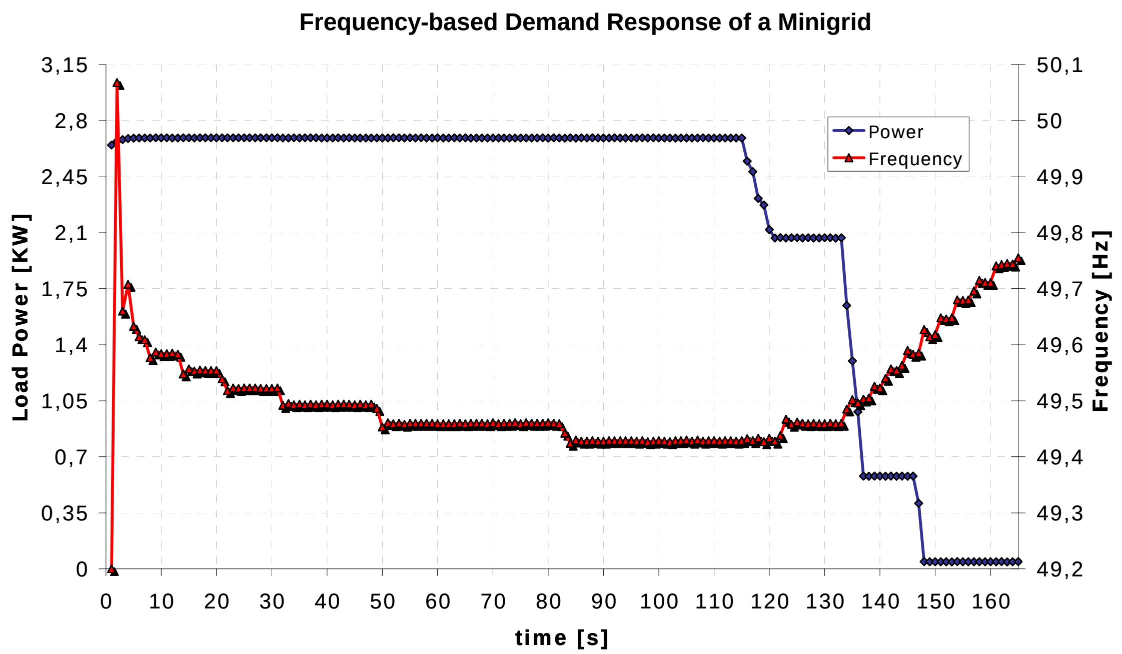


Figure 41: Results of the experiment

The new frequency steady state of the system is 49.76 Hz. The objective of the experiment was to drive the main grid out of the manual load shedding range, which begins at 49.75Hz after 5min. This situation is stable and can be supported during the necessary time while the main grid changes the set points of its generators and the system recovers the 50Hz steady state frequency.

CHAPTER 8

CONCLUSION

Throughout this thesis work it can be concluded that it is feasible to use a minigrid as support element for the main grid while obtaining a reasonable economical profit. In order to achieve this, a two-level control has been developed.

The first level shows a potential increase in the economical profit of the minigrid by participating in the day-ahead energy market and therefore helping the main grid operator in scheduling the electricity production. The increase of the benefit is mainly related to: The price of the electricity, as it is possible to buy the same amount of electricity to lower prices in the energy market than with a bilateral contract with the grid operator; The optimisation process, which is able to choose the best working points of the CHP units; The use of deferrable technologies, which gives another degree of freedom to this optimisation.

During the optimisation process it has been observed that the working point of the plant does not reach the limit of the storage tanks. This suggests that the optimum operation for this case is that in which all the thermal production is consumed.

The above is however achieved at the cost of increasing the complexity of the minigrid’s control system. A secure connection with the energy market, a PC running the optimisation algorithm and qualified personal able to understand the system are some of the new requirements.

A second downside is the dependency of the system on the forecast of the energy demand. If the forecast is not accurate, this deviation can impact in a lower economical profit.

The second level has proved to be effective in stabilizing the frequency of the main grid when small disturbances are presented. However, the range in which this can be seen is quite small. Only when the power unbalance of main grid drives the generators close to their saturation point, the minigrid is able to change the steady state point.

The results of the experiment performed show how a minigrid which represents a 1% of a grid can help it in case the frequency drops out of acceptable margins. The minigrid cannot recover the the 50Hz frequency of the main grid, although it can drive the grid out of the emergency margin.

Another downside in the use of the CMS second level is the complexity of installing relays in the different loads and controlling the time of reaction of all of them from a central point. Although, there are actually some countries, which regulations obligate the different loads to be supplied from different derived circuits. This obligation eases the implementation of these technologies.

The contribution of this work has been to demonstrate the potential of minigrids as grid support elements, by designing an energy management system able to priorize the stability of the main grid over the minigrid operation. This has been confirmed by the test of an experimental plant.

The proposed future work would be the direction of determining the proportion of minigrids necessary for stabilizing different steps of power in the main grid and the arrangement of these minigrids in the power system.

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Annex I

CMS FIRST LEVEL SOFTWARE

```
/*****************************************************************************
 *   Copyright (C) 2005 by Carlos, Antonio and Debora                        *
 *                                                                           *
 *   This program is free software; you can redistribute it and/or modify    *
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 *                                                                           *
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 *   along with this program; if not, write to the                           *
 *   Free Software Foundation, Inc.,                                         *
 *   59 Temple Place - Suite 330, Boston, MA  02111-1307, USA.               *
 *****************************************************************************/

#ifdef HAVE_CONFIG_H
#include <config.h>
#endif

#include <stdio.h>
#include <stdlib.h>
#include <math.h>


/**** COMPILER DEFINITIONS ****/
#define DIMS 12                   // CHP Setpoint possible combinations

#define INFINITO 100000000   // Definition of Infinity Price

#define HORAS 24             // Hours in a day
#define DIMSREAL 13

#define Grid_Power 2500      // kVA Main grid Connection Point
#define Z_maxCap 9326        // kWh of maximum Thermal Storage

#define Z_0 0                // Initial State of Thermal Storage [kWh]
#define Z_min 0.9*Z_0

#define HeatPrice 0.06      // Price of Heat Unit in EUR/kWh

#define OMCostBase 497      // Fixed O&M Costs
#define OMCostVar 0.01314   // Variable O&M Cost EUR/kWh


/**** CLASSES DEFINITIONS ****/
class Edge;          // In a Graph, the definition of an edge
class Vertex;        // In a Graph, the definition of a Vertex (Node)

/** BEGIN Edge Class Definition **/
/* This is just a data structure */
class Edge
{
     public:
     float weight;    // Equivalent to Price
     Vertex* dest;    // The Vertex this Edge points to
     Edge* next;      // The next Edge in the Array (0 = Last)
     int setpoint;    // Information about corresponding setpoint
};
/** END Edge Class Definition **/
```

```
/** BEGIN Vertex Class Definition **/
/* Another Class Definition     */
class Vertex
{
     public:
     Edge* connections;      // Points to the array of Edges deriving from this Vertex
     float distance; // Distance (Cost) from initial node
     float fuel;      // Fuel Cost so far
     Vertex* next;    // Next Vertex in the Array (0 = Final Vertex)
     int setpoint;    // Information about Setpoint that gives distance.
     Vertex* prev;    // Previous Node
     float LaZ;       // Stores node's Z(t): the state variable
     short deep;      // Hour of which this node is member
     float G_t;       // Electricity Sold/Bought to Main Grid

     long count;      // Node ID
     void addEdge(Vertex* siguiente, float costo, int setpoint);
                      // Adds an edge from this Vertex to vertex siguiente.
     Vertex* gotcha(float enZ, int hora);
                      // Returns a Vertex that has same Z in a given hour.
};

/** addEdge adds a new Edge (path) to the current Vertex object**/
void Vertex::addEdge(Vertex* siguiente, float costo, int setpoint)
{
     Edge* saltarin;
     if (connections != NULL)
     {
          saltarin = connections;

          while(saltarin[0].next != 0)
          {
               saltarin = saltarin[0].next;
          }
     }

     connections = new Edge();
     connections[0].weight = costo;
     connections[0].dest = siguiente;
     connections[0].next = 0;
     connections[0].setpoint = setpoint;
}

/** gotcha looks at all the children of this vertex to see if ther is one that**/
/** has the same Z at the same time, to avoid duplicating nodes. Returns the  **/
/** Vertex that complis with the citeria or NULL if none.            **/

Vertex* Vertex::gotcha(float enZ, int hora)
{
     if (next != NULL)
     {
          Vertex* saltarin;
          saltarin = next;
          do
          {
               if ((saltarin[0].LaZ == enZ)&&(hora == saltarin[0].deep))
               {
                    return saltarin;
               }
               if (saltarin[0].next!=NULL)
                    saltarin = saltarin[0].next;
               else
```

```
                    return NULL;
          }
          while (saltarin[0].next != NULL);

     }

     return NULL;
}
/** END Class Vertex definition **/

/** BEGINS Function readLine                         **/
/* This function reads from a file the selected line with HORAS hours    */
void readLine (int dataStructure[HORAS], FILE *f, char* format)
{
     char nom[10];
     fscanf(f, "%s", nom);
     printf ("%4s ", nom);
     for (int t=0; t<HORAS; t++)
     {
          fscanf(f, "%d", &(dataStructure[t]));
          printf(format, dataStructure[t]);
     }
     printf("\n");
}

void readLine (float dataStructure[HORAS], FILE *f, char* format)
{
     char nom[10];
     fscanf(f, "%s", nom);
     printf ("%4s ", nom);
     for (int t=0; t<HORAS; t++)
     {
          fscanf(f, "%f", &(dataStructure[t]));
          printf(format, dataStructure[t]);
     }
     printf("\n");
}
/** END Function readLine **/

/****        GLOBAL VARIABLE DECLARATION      ****/
/* These are variables used through the program */

int SUMAXY[DIMSREAL];         // CHP Possible Setpoints
float COSTOXY[DIMSREAL];      // CHP OPeration Costs
float PriceElCHP = 0;         // Price of Electricity
float thermEnergy = 0;

// Structure to save Excel Sheet Values
int A[HORAS];
int B[HORAS];
float Pf[HORAS];
float Pe[HORAS];
float Pu[HORAS];           //Precio de Venta a la Universidad
float Pv[HORAS];           //Precio de Venta a la Red
float C[HORAS];
float T[HORAS];
float E[HORAS];
float F[HORAS];
float H[HORAS];            // ALERTA H[-1] deber  existir
float om[HORAS];           // idem

// Calculated Array
double G[HORAS];
```

```c
/**** FUNCTION cargar_datos() will load Excel and initialization Values ****/
void cargar_datos()
{
     int t;
     FILE *f;
     char nom[10];

     // Specific Energy Consumption (L/kWhe) from CHP's datasheets
     COSTOXY[0] = 0.00000;  COSTOXY[1] = 0.24027;  COSTOXY[2] = 0.24026;
     COSTOXY[3] = 0.24219;  COSTOXY[4] = 0.24282;  COSTOXY[5] = 0.24344;
     COSTOXY[6] = 0.24737;  COSTOXY[7] = 0.24471;  COSTOXY[8] = 0.24444;
     COSTOXY[9] = 0.24515;  COSTOXY[10] = 0.24535; COSTOXY[11] = 0.24551;
     COSTOXY[12] = 0.24737;

     // Possible Combinations of the CHP setpoints (>60% in 6 levels for CHP1 and
     // 6 levels for CHP2 when CHP1 is full power
     SUMAXY[0] = 0;    SUMAXY[1] = 60;   SUMAXY[2] = 70;     // CHP Setpoints
     SUMAXY[3] = 75;   SUMAXY[4] = 80;   SUMAXY[5] = 90;
     SUMAXY[6] = 100;  SUMAXY[7] = 160;  SUMAXY[8] = 170;
     SUMAXY[9] = 175;  SUMAXY[10] = 180; SUMAXY[11] = 190;
     SUMAXY[12] = 200;

     // Begins reading of file
     f = fopen("datos", "r");
     if (f==NULL)
          printf("ERROR AL ABRIR ARCHIVO DE DATOS\n");
     else
     {
          printf("\n--- DATA INPUT ---\n");
          printf("    |  0  |  1  |  2  |  3  |  4  |  5  |  6  |  7  |",
               "  8  |  9  |  10 |  11 |  12 |  13 |  14 |  15 |  16",
               " |  17 |  18 |  19 |  20 |  21 |  22 |  23 |\n");
          readLine(A, f, "%5d ");       // A
          readLine(B, f, "%5d ");       // B
          readLine(Pf, f, "%0.3f ");    // Pf
          readLine(Pe, f, "%0.3f ");    // Pe
          readLine(Pu, f, "%0.3f ");    // Pu
          readLine(Pv, f, "%0.3f ");    // Pv
          readLine(C, f, "%5.0f ");     // C
          readLine(T, f, "%5.0f ");     // T
          readLine(E, f, "%5.0f ");     // E
          readLine(F, f, "%5.0f ");     // F
          readLine(H, f, "%5.0f ");     // H
          readLine(om, f, "%4.1f ");    // om
     }
}

void calcular_inicio()
{
     float elec_gen = 0;     // The electricity Generated

     for (int i = 0; i < HORAS; i++)
     {
          thermEnergy += T[i];
          elec_gen += T[i] * (float(B[i])/float(A[i]));
     }

     PriceElCHP = (OMCostBase / elec_gen) + OMCostVar
             - ((HeatPrice*thermEnergy)/elec_gen); // Sets CHP Price

}
```

```
/**** FUNCTION createGraph(int deep) Creates the graph of the problem  ****/
/**** and AT THE SAME TIME it will solve the problem.                  ****/
Vertex* createGraph(int deep)
{
     long count = 0;      // Node counter
     short hora=0;
     Vertex* inicio;      // The Origin Vertex
     printf ("\nProcesando hora:      \n");
     Vertex* anterior;
     Vertex* solution = new Vertex[HORAS+1]; // Stores the solution Values

     hora = 0;

     inicio = new Vertex();  // Defines what the Origin Vertex looks like
     /* According to Dijkstra's Algorithm the first node should have a
        distanc equal to 0 (the origin) */
     inicio[0].distance = 0;
     inicio[0].next = NULL;
     inicio[0].LaZ = Z_0;
     inicio[0].deep = hora;
     count++;
     hora++;

     anterior = inicio;

     Vertex* vater;
     vater = inicio;
     Vertex* minimo_aqui = new Vertex();
     minimo_aqui[0].distance = INFINITO + 10;

     /* This is the tree filling algorithm, it will calculate the children nodes
        based upon certain conditions and using certain equations which can be
        found in Chapter 4*/
     while(hora < deep)
     {
          vater = inicio;

          while (vater[0].deep != hora-1)
          {
               vater = vater[0].next;
          }
          while (vater[0].deep==hora-1)
          {
               int hijos=0;
               int nuevos=0;
               int conexiones =0;
               float Z_exceeded = 0;

               for(int i = DIMSREAL-1; i >= 0; i--)
               {
                    int z;
                    /* Calculates the Z at a given time with a given setpoint */
                    z =((int)(((A[hora-1]*(SUMAXY[i]/100.0)) + C[hora-1]
                     - T[hora-1] + vater[0].LaZ)/5))*5;
                    int noChild = 0;
                    Z_exceeded = 0;

                    if (z > Z_maxCap)
                    {
                         Z_exceeded = z - Z_maxCap;
                         z = Z_maxCap;
                    }
```

```
/*IMPORTANT! It will only create nodes in which Z is
  positive (physically there cannot be Z < 0 */

/*OTHER IMPORTANT THING! No nodes will be created if they
  exceed the Grid's power*/
if ((z >= 0))
{
     float costoCHPe = 0.0;
     float ventaCalor = 0.0;
     float impCalor = 0.0;   //Heat import
     float costo = 0;
     float Gp = 0;

     // Calculates the G. i.e. the electrical energy
     // bought/sold to the grid
     if (hora == 1)
          Gp = F[hora-1] + (om[hora-1]*H[hora-1])
            - E[hora-1]
            - (B[hora-1]*(float)(SUMAXY[i])/100.0);
     else
          Gp = F[hora-1] + (om[hora-1]*H[hora-1])
            + ((1 - om[hora-2])*H[hora-2])
            - E[hora-1]
            - (B[hora-1]*(float)(SUMAXY[i])/100.0);

     if ((Gp <= Grid_Power) && (Gp >= -Grid_Power))
     {
          hijos++;
          Vertex* siguiente;

          if ((siguiente = vater[0].gotcha(z, hora)) == NULL)
          {
               nuevos++;
               siguiente = new Vertex();
               siguiente[0].distance = INFINITO;
               siguiente[0].fuel = 0;
               siguiente[0].next = NULL;

               siguiente[0].LaZ = z;
               siguiente[0].G_t = Gp;

               siguiente[0].deep = hora;
               siguiente[0].count = count;
               siguiente[0].setpoint = -1;
               anterior[0].next = siguiente;
               count++;
               anterior = siguiente;
          }

          float costos = (OMCostBase / HORAS)
                 + ((OMCostVar + (Pf[hora-1]*COSTOXY[i]))
                 *B[hora-1]*(SUMAXY[i]/100.0));

          float deferred;
          if (hora == 1)
          {
               deferred = 0;
          }
          else
          {
               deferred  = ((1-om[hora-2])*H[hora-2]);
          }
```

```
                        float ganancias = (HeatPrice * T[hora-1])
                               + (Pu[hora-1]*(F[hora-1]
                               + (om[hora-1]*H[hora-1])
                               + deferred));

                        if (Gp >= 0)
                        {
                             costo =  (Gp*Pe[hora-1]) + costos - ganancias;
                        }
                        else
                        {
                             costo =  (Gp*Pv[hora-1]) + costos - ganancias;
                        }

                        /*Acaba Calculo de Costes */

                        if (vater[0].distance + costo
                            < siguiente[0].distance)
                        {
                             siguiente[0].distance = vater[0].distance
                                         + costo;

                             siguiente[0].fuel = costos;
                             siguiente[0].setpoint = SUMAXY[i];
                             siguiente[0].prev = vater;
                             siguiente[0].G_t = Gp;
                        }

                        if ((siguiente[0].distance < minimo_aqui[0].distance)
                          && (siguiente[0].deep == deep-1)
                          && (siguiente[0].LaZ > Z_min))
                        {
                             minimo_aqui = siguiente;
                        }

                        vater[0].addEdge(siguiente, costo, SUMAXY[i]);
                        conexiones++;
                   }
              }
              else
              {
                   break;
              }
         }

         if (vater[0].next != NULL)
         {
              vater = vater[0].next;
         }
         else
         {
              printf("No feasible solution found at hour %i\n", hora);
              return NULL;
         }
    }

    printf("%2i (%6li nodes)\n", hora-1, count);
    hora++;
}

/* THIS ONE PRINTS THE SCHEDULE ON SCREEN*/
while(minimo_aqui)
{
```

```
          solution[minimo_aqui[0].deep] = minimo_aqui[0];
          minimo_aqui = minimo_aqui[0].prev;
     }

     return solution;
}

/** int main() is the main function **/
int main()
{
     Vertex* solution;

     cargar_datos();
     calcular_inicio();
     solution = createGraph(25);
     FILE* salida = fopen("debora.csv", "w");

     fprintf(salida, "G,X,Y,Z,Omega,Cost \n");

     for(int c = 1; c <= HORAS; c++)
     {
          fprintf(salida, "%5.0f,%d,%d,%5.0f, %0.3f,%6.2f\n", solution[c].G_t
               , (solution[c].setpoint/101)*100
               , (solution[c].setpoint%101)+(solution[c].setpoint/101)
               , solution[c].LaZ, om[c-1], solution[c].distance);
     }
     printf("\n");
     //prints all
     printf ("\b\nSETP ");
     for(int c = 1; c <= HORAS; c++)
     {
          printf("%5d ", solution[c].setpoint);
     }

     printf ("\nZ    ");
     for(int c = 1; c <= HORAS; c++)
     {
          printf("%5.0f ", solution[c].LaZ);
     }
     printf("\n");

     printf ("\nEUR  ");
     for(int c = 1; c <= HORAS; c++)
     {
          printf("%5.0f ", solution[c].distance);
     }
     printf("\n");

     printf ("\nG(t) ");
     for(int c = 1; c <= HORAS; c++)
     {
          printf("%5.0f ", solution[c].G_t);
     }
     printf("\n");

          printf ("Neto ");
     for(int c = 1; c <= HORAS; c++)
     {
          printf("%5.0f ", solution[c].fuel);
     }
     printf("\n");
     return EXIT_SUCCESS;
}
```

Annex II

CMS SECOND LEVEL SOFTWARE

```
public class PruebaClass
{
	private static ISETSQLService servicio;
	private static String log_keyfield;
	private static String P_nom_SI;
	private static int hola;

	private static int defer;
	private static int n_defer;
	private static int light;


	public PruebaClass()
	{
		System.out.println("Hello World! but you SHOULD not",
				" use this class other than as main Class");
	}

	private static double getFreq()
	{
		double toReturn = -1;

		try
		{
			toReturn = servicio.getNumber("ld_load1_log",
"Ain_C",log_keyfield);

			if (hola%10==0)
			inform("Frequency: "+toReturn+" Hz");

			hola++;

		}catch(Exception e){inform("Got error while reading",
					" Frequency:
"+e.getLocalizedMessage());}

		return toReturn;
	}

	private static void siesta(int tiempo)
	{
		try
		{
			Thread.sleep(tiempo*1000);
		}
		catch(InterruptedException e){inform ("Riiiiiiiiing!");}
	}

	private static void siestita(int tiempo)
	{
		try
		{
			Thread.sleep(tiempo*100);
		}
		catch(InterruptedException e){inform ("Riiiiiiiiing!");}
	}


	/**
	 * Sets or clears the operation bit of Relay_n
	 *
	 * @param status "0" to open, "1" to close
	 * @param number Number of Relay
	 */
	private static void changeRelay(String status, int number)
	{
		try
		{
		    servicio.putData("ld_load1_con", "Relay_"+number,
status);
		}catch(Exception e){inform("Got error while setting",
						Relay"+number+" to:
"+status);}
	}
```

```
        private static void changeRelay(String status, String who)
        {
                try
                {
                        servicio.putData("ld_load1_con", who, status);
                }catch(Exception e){inform("Got error while setting",
                        "Relay"+who+" to: "+status+e.getLocalizedMessage());}
        }

        private static void islandManager (int status, String P, String Q)
        {
               inform ("Sunny Mallorca: Setting me to: " + status +" with P: "
                                     + P + " and Q: "+Q);

                try
                {
                        servicio.putData("ld_storage1_con","Start_Stop,” ,
                                          " GridSync, Pset, Qset","1, 1,
"+P+", "+Q);
                }catch(Exception e){inform("Sunny Mallorca died: "

+e.getLocalizedMessage());}

        }

        public static void inform(String str)
        {
                System.out.println("MAIN: " + str);
        }

        private static void startCMS2()
        {
                int contLoads = 0;       // Counter in CMS level 2
                inform("Entering CMS Level two. Close your eyes and”,
                                 "
enjoy....");


                        // Beginning load shedding
                        inform("Beginning Load Shedding... uy");

                        contLoads=0;
                        while(contLoads <= 150)
                        {
                                double frequency = getFreq();

                                if(frequency <= 49.75 && defer==1)
                                {
                                        changeRelay("0, 0, 0", "Relay_4,”,
                                                               "Relay_5,
Relay_6");
                                   // IMPORTANTE!!!! Relay1 desactiva
deferrable
                                        inform("Disconnected
Deferrables");
                                        contLoads=0;
                                        defer=0;
                                }

                                if(frequency <= 49.70 && n_defer == 1)
                                {
                                        changeRelay("0, 0, 0", "Relay_1,”,
                                                                "Relay_2,
Relay_3");
                          // IMPORTANTE!!!! Relay2 desactiva non-deferrable
                                        inform("Disconnected non”,
                                                                         "
-Deferrable");
                                        contLoads=0;
                                        n_defer = 0;
                                }

                                if(frequency <= 49.50 && light == 1 )
                                {
                                        changeRelay("0", "Relay_8");
```

```
                                    // IMPORTANTE!!!! Relay2 desactiva
Lighting
                                        contLoads=0;
                                        inform("Disconnected Lighting. Oh
oh!");
                                        light = 0;
                              }

                              if(frequency > 49.75)
                              {
                                        contLoads++;
                                        switch(contLoads)
                                        {
                                                  case 60:
inform("Reconnecti",
         "ng Lighting.");
                                                            changeRelay("1",
"Relay_8");
                                                            light = 1;
                                                            break;

                                                  case 90:
inform("Reconnecti",
                                                                  "ng non-
Deferrable.");
                                                            changeRelay("1,
1,
                                                  1", "Relay_1, Relay_2,
Relay_3");
                                                            n_defer = 1;
                                                            break;

                                                  case 120:
inform("Reconnecti",
                                                                  "ng
Deferrables.");
                                                            changeRelay("0,
0,",
                                                  " 0", "Relay_4, Relay_5,
Relay_6");
                                                            defer = 1;
                                                            break;

                                        }
                              }
                              siestita(10);
                    }
                    inform("All loads are reconected... UIB full
power");

                    islandManager(1, "0.0" , "0.0");

          }

          public static void main(String[] args)
          {
                    hola = 0;
                    int a=0;
                    inform ("ISET-Mallorca experiment... Hello!");
                    P_nom_SI = "200"; //W

                    defer = 1;
                    n_defer = 1;
                    light = 1;

                    double lowf = 41;
```

```
                    double hif = 59;

                    try
                    {
                              servicio = new ISETSQLService("127.0.0.1",....);


                              log_keyfield = "LOG_ID";

                              int espera = 0;
                                                // Time to wait until switching CMS
Level 2
                              int restore = 0;  // Counter for restoring the
system



                              while(a!=1)
                              {

                                        if (getFreq() <= 49.75)
                                        {
                                                  inform("Oh oh, things are going",
                                                " creepy in the Grid, is it really so
bad?");
                                                  siesta(60);
                                                  if(getFreq()<= 49.75)
                                                  {
                                                            inform("Holly cow! Got
to",
                                                                            " do
something...");
                                                            startCMS2();
                                                  }
                                        }
                                        siesta(1);
                              }

                              inform("Closing connection");
                              servicio.finalize();
                              inform("The End");

                    }catch(Exception e)
                              {System.out.println(e.getLocalizedMessage());}
          }
}
```

Annex III

SET UP OF A GRID SIMULATOR

This work presents the modifications in the control of the DC machine in order to convert a system composed by a DC machine and a synchronous generator in a grid simulator.

Control of the DC machine

The original control of the DC machine, see on figure 1, sets the frequency at a fixed frequency of usually 50Hz. When the torque demanded by the synchronous generator on the DC machine grows up, the DC machine rapidly increases the power output in order to compensate it.

In this control the effect of the grid is, at this stage, not contemplated.

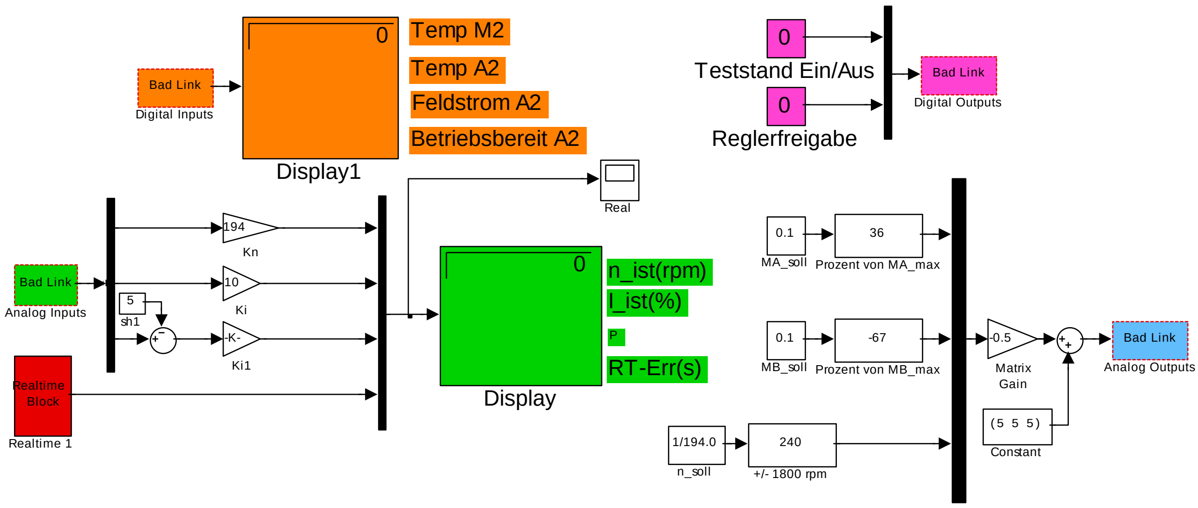

Figure 1: Matlab Control tool of the DC generator

Control of the Grid Simulator

The idea proposed in the development of the new control tool is to control the frequency so that it represents the variation that a grid would show. Also considering lines, loads and other generators.

In order to reach this, a modification on the frequency input is proposed. The frequency set point is not a constant anymore but a new block which represents the behaviour of whole grid. The input to this block is the power demand, as well as a steady state power and frequency of the system and the output is the frequency answer of the grid, see on figure 2.

In the experiment carried out, the main grid was the IEEE 14 Bus case study. Therefore, the configuration of this control corresponds to this grid.

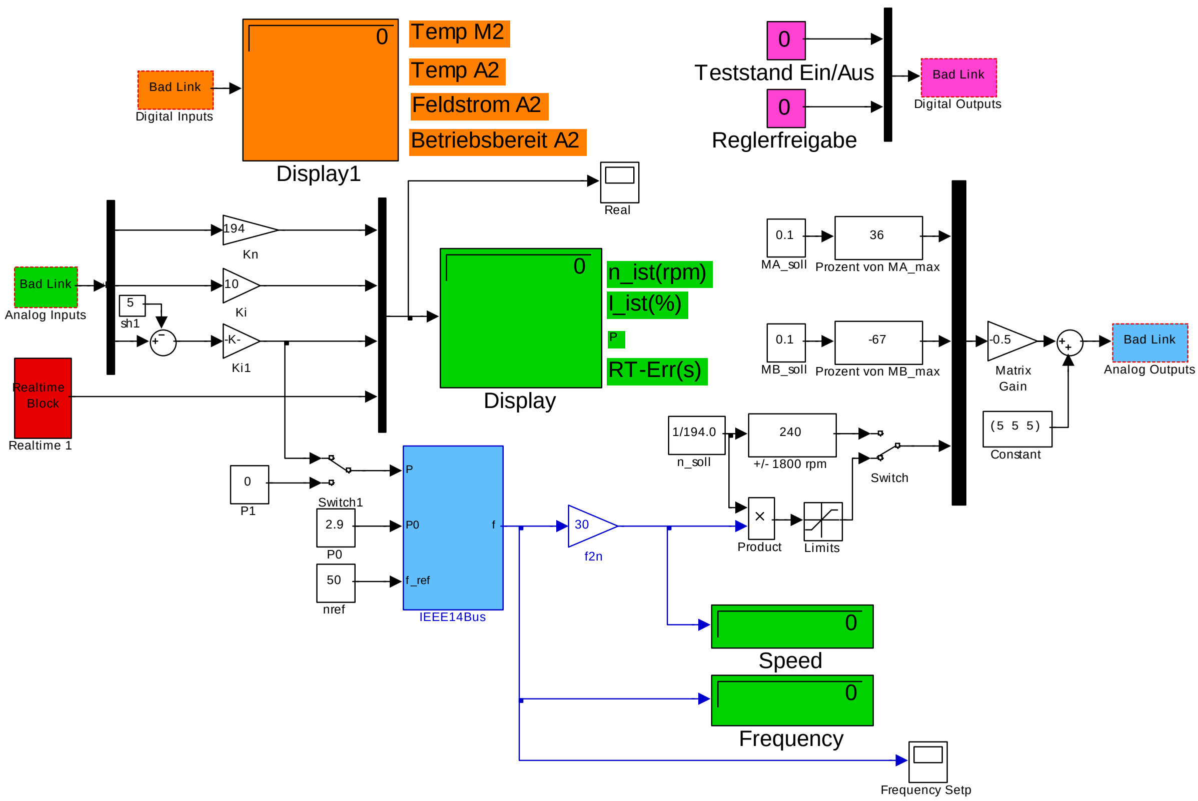

Figure 2: Matlab Control block of the grid simulator

The new block called IEEE 14bus represents the grid behaviour. The grid is simulated with linear differential equations, which are applicable to studies of small disturbances. Therefore, the inputs and outputs to the grid model are considered as deltas and not absolute values. ΔP is the power input and Δf the frequency output. The block, shown in figure 3, converts the value of the direct measurement of the power in a ΔP, by taking away a $P_{reference}$ called P_0, and the Δf obtained in the calculation by adding a $f_{reference}$. The value of P_0 is the value of the steady state power in the system, in this experiment was 2.9kW. The $f_{reference}$ is the steady state set point of the frequency, usually 50Hz.

The model of the grid was developed in a per-unit system because of that, the ΔP must be divided by the base power of our system, this conversion is done by using the gain block shown. In this case the base power of the system is 140kVA.

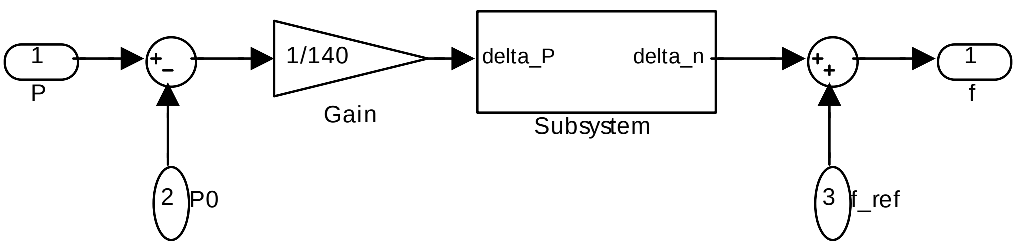

Figure 3: IEEE 14bus block

Once the data is converted to the required format, the grid is simulated with the block “subsystem”. This block contains the above mentioned equations that represent the grid, see figure 4.

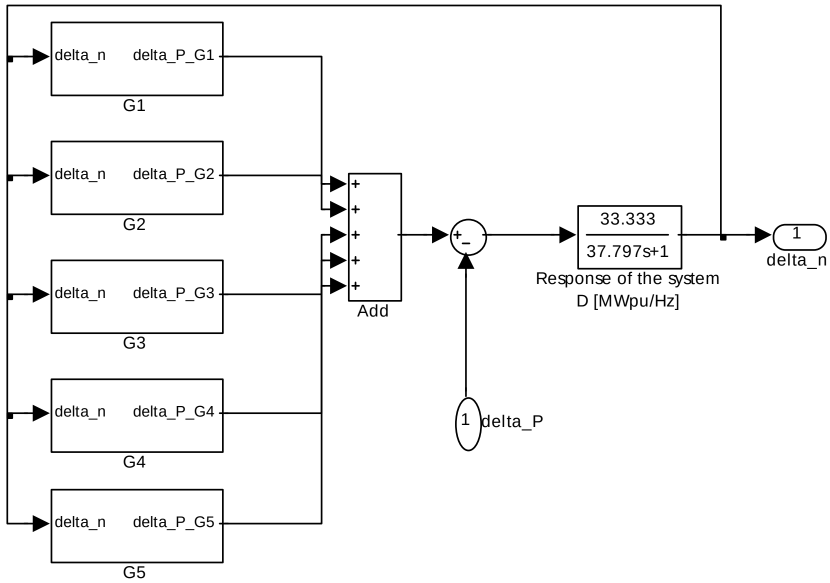

Figure 4: IEEE 14bus block subsystem

The grid is built up with 5 generators, the different generators have specific characteristics, which can be seen opening their tool boxes. The D value of the grid was calculated using ATP, the result is given as transfer function.

As example one of the generators tool box is given in figure 5.

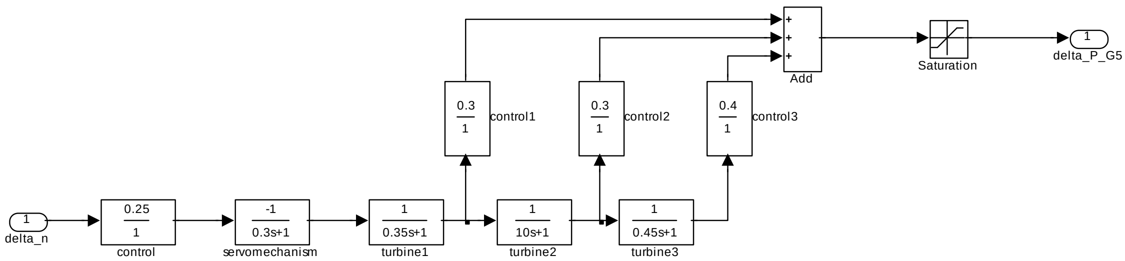

Figure 5: generator G5, it is a combined cycle with three turbines, of high and low pressure

Simulating the control behaviour

With a step of power of 42kVA, the simulation with matlab of the behaviour of the frequency in the created grid with the available control, can be seen in figure 6, with the new control is given in figure 7.

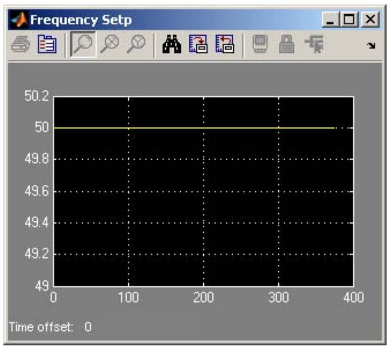

Figure 6: DC motor control

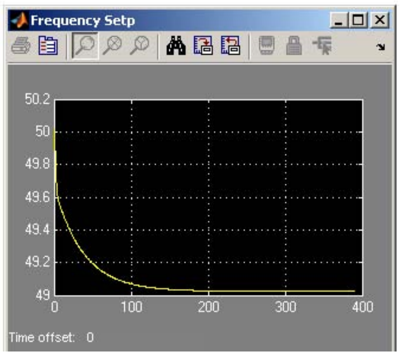

Figure 7: new control