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INTEGRATION OF DISTRIBUTED GENERATION USING ENERGY STORAGE SYSTEMS

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Abstract

New challenges in grid reliability are coming up with the increasing penetration of renewable energies and distributed generation (DG). The use of Energy Storage Systems (ESS) is proposed in this thesis as solution for different problems related to these new challenges.

The development and current state of ESS are described in this thesis. This description permits to choose the best solution for the different scenarios that are analyzed.

The analysis of electrical grids is carried out by means of simulation tools. For this purpose a dynamic power calculation is proposed. The modeling of electrical components and their implementation in the proposed simulation tool permits to analyze the frequency and voltage stability of power systems. These two are the most important parameters for grid operation and therefore the most important parameters to analyze the integration of DG.

Some applications related to the use of ESS as a solution for a certain problem related to the high penetration of DG are analyzed in the present work. Voltage regulation, restoration of large frequency deviations, primary frequency regulation and the control of the power dispatch of a wind farm are proposed as applications for ESS.

The design of an application combining these functionalities is discussed. Hybrid ESS that combines different ESS technologies is proposed as a single solution for all the applications analyzed during the course of this thesis.

Compendio

La creciente penetración de energías renovables y Generación Distribuida (GD) presentan nuevos retos en la fiabilidad de las redes eléctricas. El uso de Sistemas de Almacenamiento de Energía (SAE) se propone en esta tesis como solución a diferentes problemas derivados de los mencionados retos.

El desarrollo y el actual estado de los SAE se describen en esta tesis. Esta descripción permite elegir la mejor solución ante los diferentes escenarios que se analizan.

El análisis de las redes eléctricas se realiza mediante herramientas de simulación. Con este objetivo se propone el cálculo dinámico de los flujos de carga. El modelado de componentes eléctricos y su implementación en la herramienta de simulación propuesta permite analizar la estabilidad del voltaje y la frecuencia en los sistemas de potencia. Estos dos parámetros son los más importantes para operación de la red eléctrica y por consiguiente son los parámetros más importantes para analizar la integración de la GD.

En este trabajo se analizan varias aplicaciones relacionadas con el uso de los SAE como solución a ciertos problemas relacionados con la alta penetración de la GD. Regulación de voltaje, restitución de grandes desviaciones de frecuencia, regulación primaria de frecuencia y el despacho controlado de los parques eólicos se proponen como aplicaciones para SAE.

Se debate el diseño de una aplicación que combine estas funcionalidades. Se propone un SAE Híbrido que combine diferentes tecnologías de SAE como solución única para todas las aplicaciones analizadas durante el curso de esta tesis.

Iruzkina

Energia berriztagarrien eta Sorkuntza Barreiatuaren (SB) erabilera azkorrak erronka berriak aurkezten ditu sare elektrikoen sinesgarritasunari begira. Tesi honetan Energia Metatzeko Sistemen (EMS) erabilera eztabaidatzen da aipatutako erronketatik eratorritako zenbait arazo konpontzeari begira.

EMSen garapena eta egungo egoera azaltzen dira tesi honetan. Deskribapen honek tesi honetan aztertzen diren egoera desberdinentzat konponbide egokiena hautatzea ahalbideratzen du.

Sare elektrikoen azterketa simulaziorako tresnen bidez egiten da. Helburu hau betetzeko potentzia fluxuen kalkulu dinamikoa proposatzen da. Osagai elektrikoen modelatzeak eta beren inplementazioak proposaturiko simulazio tresnan potentziako sistemen tentsio eta frekuentziaren azterketa egitea ahalbideratzen du. Bi parametro hauek dira garrantzitsuenak sare elektrikoaren operazioaren ikuspegitik eta honenbestez parametro garrantzitsuenak dira SBren integrazioa aztertzeko orduan.

Lan honetan EMSen erabileraren inguruko hainbat aplikazio aztertzen dira, SBren sarrera handiarekin erlazionatutako zenbait arazori konponbidea bilatzeko. Tentsioaren erregulazioa, frekuentziaren desbideratze handien berreskurapena, frekuentziaren erregulazio primarioa eta parke eolikoen despatxu kontrolatua EMSentzako aplikazio bezala proposatzen dira.

Funtzio guzti hauek beteko lituzken aplikazio baten diseinua eztabaidatzen da. EMS Hibrido bat proposatzen da EMS teknologia desberdinak konbinatuko dituena, lan honetan aztertu diren aplikazio desberdinentzako soluzio bezala.

Eskerrak

Mondragon Unibertsitateari eta Ingeteam T&Dri eskertu nahi diet doktoretza tesi hau aurrera eramateko aukera eskaini izana. Bide horretan lagundu nauen Miguel Rodriguezi nire eskerrik beroenak 3 urte eta erdiko apustu honetan sartzera bultzatzeagatik eta denbora honetan guztian unibertsitatea utzi badu ere nire aldeko apustua egiteagatik. Era berean eskerrak eman nahi dizkiot Miguelek utzitako hutsunea bete eta nire tesiaren zuzendaritza eraman duen Jon Andoni Barrenari bere aholkuengatik eta lankidetzagatik.

Tesi hau hasi nuenetik nire lankide eta lagun izan ditudan Markel Zubiaga, Pello Otxandiano eta Urtzi Lazkano ere ez nituzke ahaztu nahi, hainbat ordu pasa baititugu elkarrekin azken urte hauetan, tesiaren inguruko gorabeherak eta beste hainbat gauzari buruz berriketan. Nola ez gogoan izango ditut aurrerantzean ere Garaiako lan taldea osatu duten lankide guztiak: Esti Solas, Gonzalo, Abad, Igor Baraia, Gaizka Almandoz, Gaizka Ugalde, Haritz Milikua, Jose Maria Canales, Mikel Sanzberro, Javi Poza, Dabid Garrido, Unai Iraola, Josu Aizpurua, Ander Urdangarin, Iñaki Zeberio, Mikel Oiarbide, Aitor Laka, Alain Sanchez eta ahaztuko nituen lankideak ere. Gogoan eduki nahi nuke tesia hasi nuenean departamentuko buru zen Jose Ramon Torrealdai ere.

Gogoan ditut ere Manex, Mantalax, Ayesta eta koadrilako beste lagun guztiak nire poz eta haserreak partekatzeagatik urte hauetan zehar. Tesi hau nire etxekoei eskaini nahi nien beti hor eduki ditudalako eta nire ikasketak aurrera eramateko akuilu izan direlako beti. Tamalez nire eskaintza, 2009ko udan, tesi hau burutzen ari nintzen bitartean, hil zen nire lagun Remirentzako da, “hi bai etxeako moukua”. Hala ere bizitzaren errotak aurrera jarraitzen du eta izan bedi ekarpen zientifiko hau urte bete besterik ez duen nire iloba Ametsentzako etorkizun hobe baten isla.

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List of acronyms

EU	European Union
LV	Low Voltage
MV	Medium Voltage
HV	High Voltage
DG	Distributed Generation
ESS	Energy Storage System
C	Nominal current capacity of a battery
OLTC	On-Load Tap Changer
T&D	Transmission and distribution
UPS	Uninterruptible Power Supply
SMES	Super Magnetic Energy Storage
CAES	Compressed Air Energy Storage
EDLC	Electronic Double Layer Capacitor or Ultracaps
AC	Alternate Current
DC	Direct Current
Ni-Cd	Nickel Cadmium
BESS	Battery Energy Storage System
NaS	Sodium Sulfure
US	United States of America
REDOX	Reduction Oxidation

PCS	Power Conversion System
STATCOM	Static Synchronous Compensator
DEH	Digital electrohydraulic
CCS	Coordinated Control System
AGC	Automatic Generation Control
PCC	Point of Common Coupling
AVC	Automatic Voltage Control
LDC	Line Drop Compensation
PWM	Pulse Width Modulation

Chapter 1

Introduction

1. Introduction

1.1. Framework of the thesis

In 1999, the Spanish government approved the Renewable Energies Promotion Plan, which followed the European Union (EU) guidelines set out in the 1997 White Paper on renewable energies and was then legislated in the EU Directive 2001/77/EC [1]. The EU adopted in 2007 the target of 20 % renewable energy from final energy consumption by 2020 [2]. This policy is leading to a large increase on the installation of renewable energy sources.

Together with these policies the liberalization of the electricity markets provoke the change of electrical grids [3, 4]. Traditionally electrical grids were built regarding a generation model where large power stations provide the electricity to supply all the customers. In this grid topology, the power produced by these power stations is transmitted in HV to consumption points, changing there to MV for its distribution and finally is transformed to LV for its consumption.

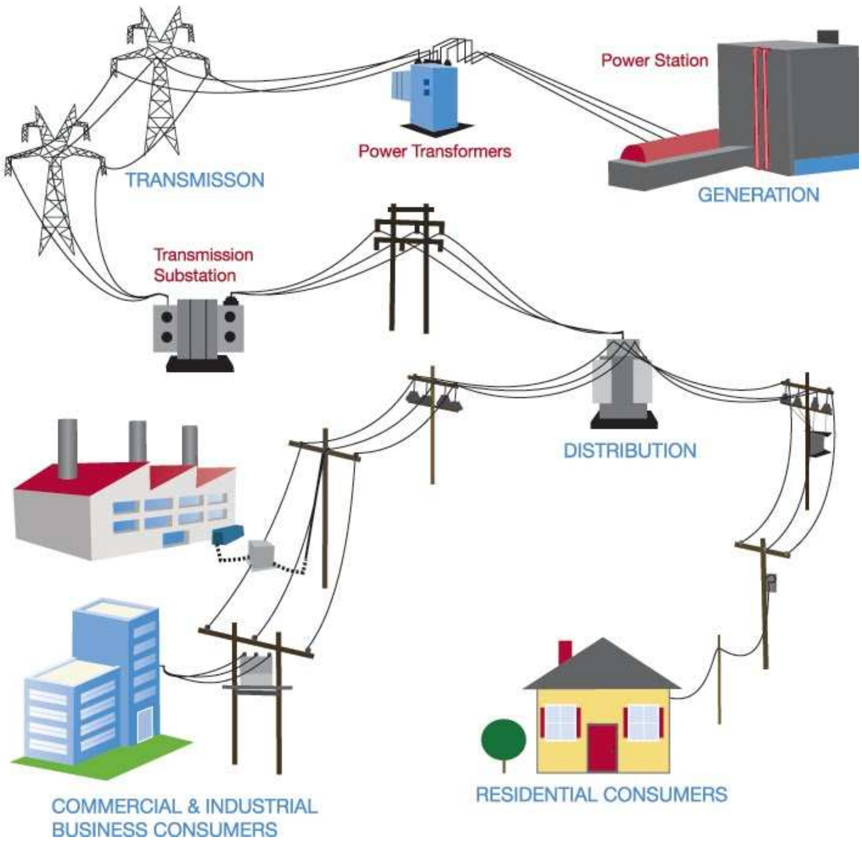


Figure 1: Centralized electrical grid topology (Source: SDM)

Even if large wind farms or hydroelectric power plants are connected to the transmission grid, a large amount of renewable energy is connected to the distribution network. These generation units can be defined as Distributed Generation (DG). The increasing penetration of DG is already changing the network topology [5]. In this new grid topology the power flow change from unidirectional to bidirectional flows. Therefore the traditional operation and regulation of the electrical grid may become insufficient and new methods will be necessary.

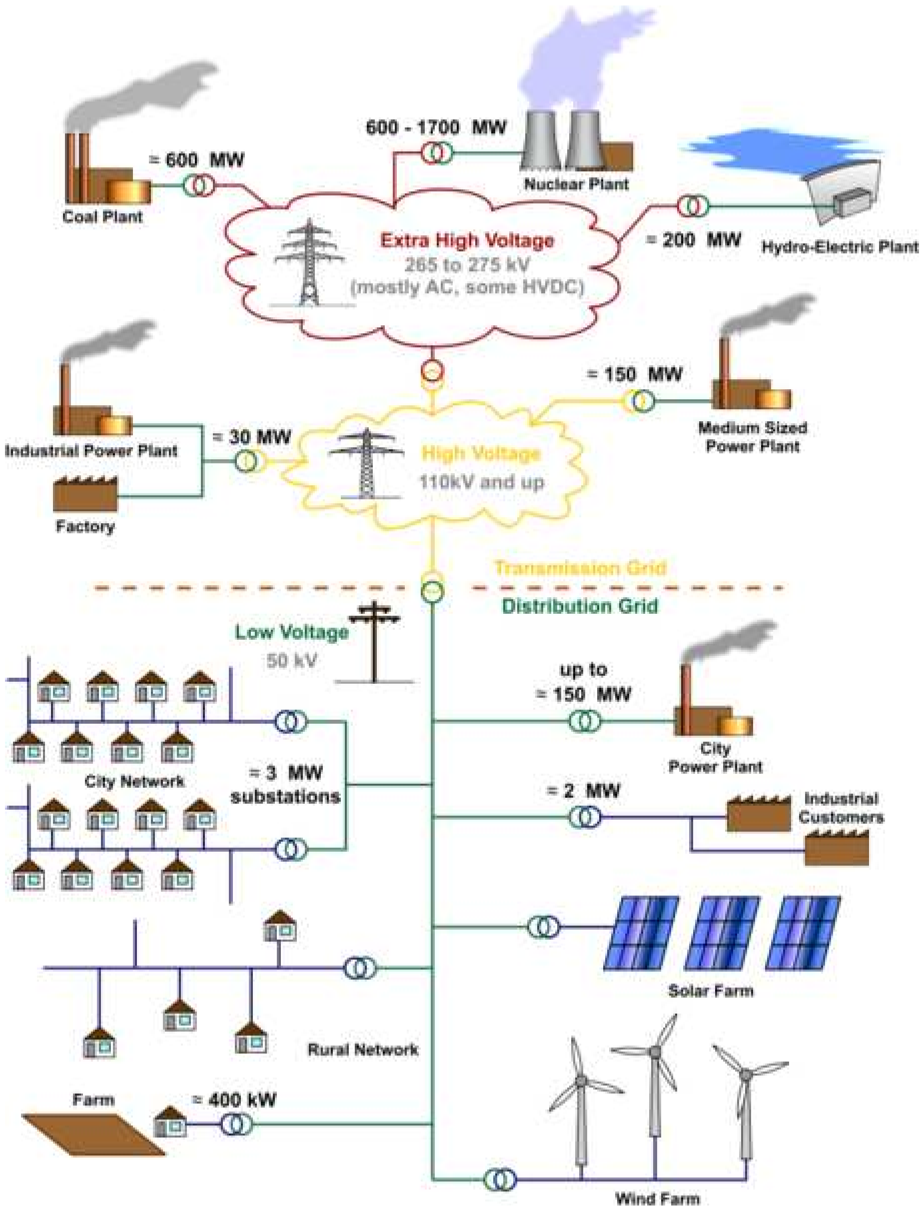


Figure 2: Electrical grid with Distributed Generation (Source: Wapedia)

Historically one of the main problems of electricity generation is the necessity to meet the electricity demand instantaneously. Due to the impossibility to store large amounts of electricity the electric power production should be sized to meet the peak demand. In this way the relationship between power production capacity and produced power is very low, around 40-50% [6].

This low capacity factor of electrical grids is turning lower with the impact of renewable energies, such as solar and wind energy. Many times these renewable resources produce their peak power when the consumption is very low, while sometimes there is not any renewable power during peak consumption periods. Therefore sufficient power from traditional generation units should be installed to supply the demand when renewable energies are not available. This is leading to an increase on the power production capacity.

By storing energy from variable resources, such as wind and solar power, Energy Storage Systems could adapt the renewable generation to the load demand and allow the produced energy to be used more efficiently [7, 8].

1.1.1. Distributed generation

On-site generation, dispersed generation, embedded generation, decentralized generation, decentralized energy or distributed energy are the different names that can be found for the concept [9] generally known as DG. As mentioned in [4, 5, 10] there are a large number of terms and definitions related to DG. Nowadays each country has defined its own legal definition of this term.

Other authors [10] define DG as, "a small source of electric power generation or storage that is not a part of a large central power source and is located close to the load". These authors also include storage facilities in the definition of DG, which is not so common. Furthermore, they stress on the relatively small scale of the generation units.

In [4] the authors take into account the following criteria in order to define the DG: voltage level at grid connection, generation capacity, services supplied, generation technology, operation mode, power delivery area and ownership. A review about the different definitions related to DG is given in [11]. After reviewing the literature about the definition of DG they conclude that the best definition is the one given in [5].

The different issues that are used to define what is DG are discussed in[5]: the purpose, the location, the rating of DG, the power delivery area, the technology, the environmental impact, the mode of operation, the ownership and the penetration of DG. For these authors the only relevant aspects to define the DG are the purpose and the technology. Eventually they propose the following definition for DG: *"DG is an electric power source connected directly to the distribution network or on the customer side of the meter"*.

However they introduce some categories of different ratings of DG: micro (<5kW), small (5kW<5MW), medium (5MW<50MW) and large (50MW<300MW).

The most important drivers for the growth of DG (DG) in recent years are: the liberalization of the electricity market and the environmental concerns [12]. On the one hand electricity suppliers are interested on DG due to its ability to respond in a flexible way to changing market conditions, on the other hand environmental regulations force players in the electricity market to look for cleaner energy solutions.

1.1.2. Operation and control of distribution grids

A properly designed and operated power system should meet the following fundamental requirements [13]:

- The system must be able to meet the continually changing load demand for active and reactive power.
- The system should supply energy at minimum cost and with minimum ecological impact.
- The quality of power supply must meet certain minimum standards with regard to the following factors:
    - constancy of frequency
    - constancy of voltage

1.1.2.1. Voltage control

Power may flow in two directions within a certain voltage level, but it usually flows from higher to lower voltage levels, i.e. from transmission to distribution grid. The massive integration of DG may change these flows and induce power flows from low to medium-voltage grid [10].

In this context the actual network operation and control methods can become insufficient in the future, since the design of these grids was made for a unidirectional power flow. One of the main obstacles for a large implementation of DG is voltage control [5, 14]. In this sense many authors have analyzed the problem of voltage control in distribution networks with high penetration of DG. In [15-17] the authors analyzed the use of OLTC (on-load tap changers) transformers to control the voltage levels in the MV distribution grids, in presence of a high level of DG. Due to the increasing penetration of DG in the LV distribution network the control of these grids becomes more complicated, since there are not anymore passive networks. In fact, it seems to be necessary the control of the voltage levels in these networks.

Other authors [18] discussed about the use of inverters for voltage control applying reactive power compensation. The use of OLTCs together with reactive power compensation is discussed in [17].

1.1.2.2. Frequency control

The increasing penetration of distributed generation (DG) in the electricity grid will result in a reduction of the number of connected conventional power plants, which are nowadays responsible for control of the electricity network frequency. Currently most of DG units do not contribute to frequency control [19]. However, in recent years many grid codes demand to DG owners their contribution on frequency regulation. Therefore, the connection of an increasing number of DG units should be carefully evaluated and planned upfront [12].

A significant part of the DG units will be connected to the grid with power electronic converters. This gives these generators a behavior that is fundamentally different from the conventional generators. Some types of DG units supply a DC current (fuel cells, solar cells), which is converted to AC by the converter. They are ‘inertia-less’ and they have no direct relation between power and frequency. Other types of DG unit are based on machines (wind turbines, micro turbines), but the converter decouples their rotational speed from the grid frequency to make variable speed operation possible. And therefore they also do not have the direct relation between their inertia and the grid frequency. So, all these DG units will not contribute to the inertial response. A control loop can be implemented in some cases however, to give these DG units a ‘virtual inertia’[20].

Energy storage systems offer additional or alternative measures to traditional means of maintaining adequate generation reserve to mitigate load-generation imbalances (frequency contingencies). Storage systems are particularly better suited for primary frequency control and secondary frequency control, which both require prompt response time and limited deployment time (unlike conventional generators, energy storage technologies can easily provide fast response) [21].

1.1.3. Energy Storage Systems for the integration of Distributed Generation

There are some technologies to transform and store the electrical energy. These technologies are considered Energy Storage Systems (ESS). There are different technologies depending on the type of energy that electricity is transformed to: batteries, Ultracaps, flywheels, SMES, CAES or hydroelectric storage.

The use of Energy Storage Systems to solve problems related to the massive integration of DG is becoming an interesting issue [22-26].

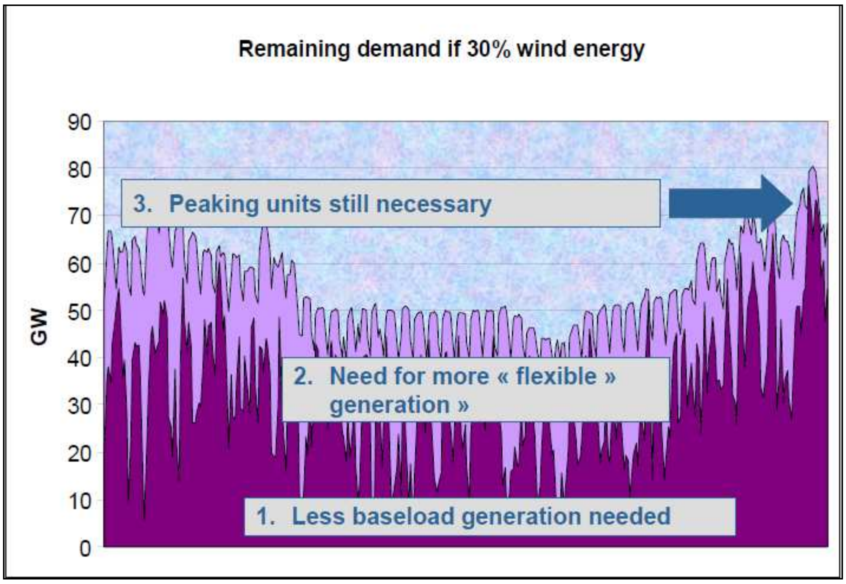


Figure 3: Impact of DG in the electrical grid. Source: EDF R&D, European Workshop on Energy Storage

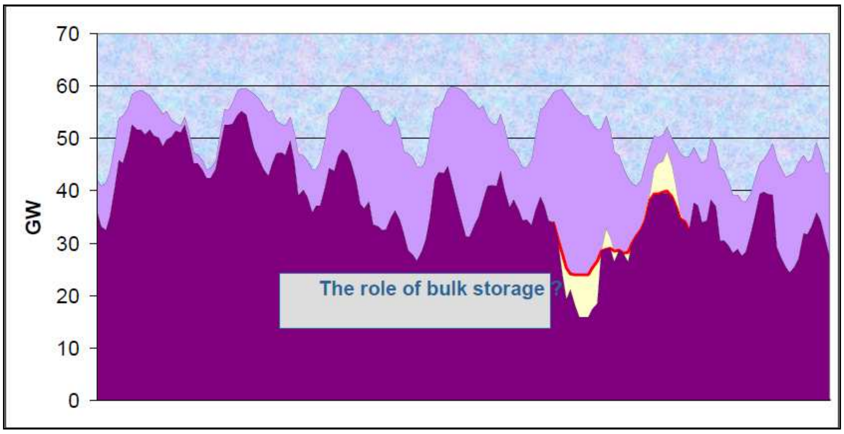


Figure 4: Contribution of ESS. Source: EDF R&D, European Workshop on Energy Storage (November 2009)

Figure 3 and Figure 4 show a study made in France, in which the load demand in France during 2007 is shown in light purple and the necessary traditional generation (nuclear, combined cycle, hydro…) if the 30% of the energy would be supplied by wind energy is shown in dark purple. Figure 4 shows the possible contribution of Energy Storage Systems in this context.

Performance parameters of storage devices are often expressed in a wide variety of terms and units. Each technology has some inherent advantages and limitations/disadvantages that make it practical or economical for only a limited range of applications. For large-scale stationary electrical power storage, the applications can be divided into three major functional categories [22]:

- Power Quality: in these applications, stored energy is only applied for seconds or less, to ensure continuity of quality power.
- Bridging Power: stored energy is used for seconds to minutes to ensure continuity of service when switching from one source of generation to another.
- Energy Management: storage is used to decouple the timing of generation and consumption of electric energy. A typical application is load leveling, which involves the charging of storage when energy cost is low and discharging the energy when it is needed. This would also enable consumers to be grid-independent for many hours.

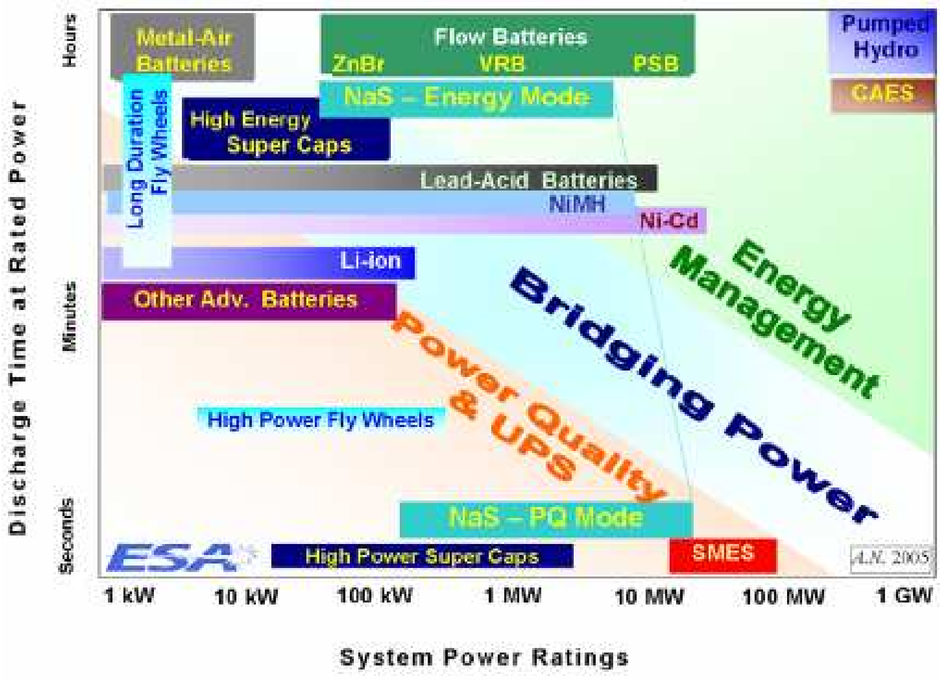


Figure 5: Classification of ESS. Source: Electricity Storage Association (ESA)

For Power Quality applications fast response ESS technologies like SMES (Superconducting Magnetic Energy Storage), Flywheels or Ultracaps are used normally [27, 28], but also some battery technologies may be suitable for these applications [29, 30]. For Bridging Power applications like UPS batteries and flywheels are used normally [30]. For Energy Management applications hydro and compressed air storage technologies are the cheapest solutions, but for smaller storage rates as it is the case of renewable energies batteries are a good solution. In this thesis Power Quality and Energy Management applications are analyzed.

The electricity supply industry has three main sectors the generation, the transmission and distribution (T&D) and the customer services. Within these three sectors up to thirteen applications may be identified. Although many of these applications may be covered with generators, ESS may respond to applications in the three sectors. For example a battery system may contribute in different applications like power reserve, load following, deployment of investments on new generators or even frequency regulation. In other conditions, a battery system may contribute on the deployment of investment in a MV substation while controls the voltage. For customers a single battery may contribute to improve the power quality and peak shaving. The thirteen applications that are identified for the use of Energy Storage Systems are the followings:

Generation

1) Generation reserve: reserve of generation capacity to avoid the interruption of service in the face of grid or equipment failures. Generation centers should have power generation reserve to substitute the largest generator in the face of failures. The generation reserve is expensive, because generators should work under their optimal performance. Energy Storage Systems may be a cheaper solution to supply this reserve.

2) Deployment of investments in capacity: possibility to postpone the installation of new generation centers installing Energy Storage systems. The generated power is stored during low consumption periods to be supplied during consumption peaks.

3) Area/Frequency control: give capacity to interconnected grids to limit unpredicted power transmissions to neighbor grids (area control) and maintain the frequency stability (frequency control). In normal conditions each grid should supply the energy to its customers without receiving/supplying energy from/to other areas. In this way each system contributes equally to balance the frequency. Energy Storage Systems may contribute in this application varying the power output every minute following the load profile of the system.

4) Renewable energies: applications in which renewable energies are available during consumption peaks or/and at constant level. Although renewable energies are abundant its nature requires the adjustment of the generation with the demand. Using Energy Storage Systems renewable energy might be stored in case of generation surplus to supply this energy in periods of high consumption or high electricity price.

Figure 6: ESS to stabilize intermittent renewable energies. Source: NGK insulators.

5) Load leveling and peak shaving: store the electricity at low cost during consumption valleys to supply it during demand peaks. Grid operators can make important savings reducing or leveling consumption peaks.

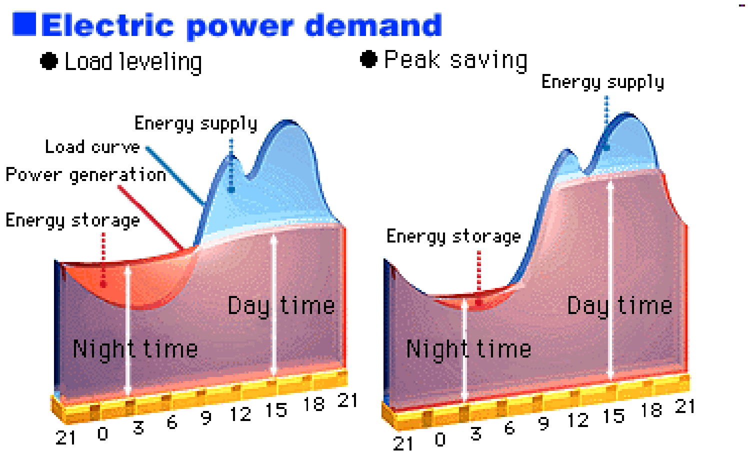


Figure 7: Load leveling and peak shaving applications for ESS. (Source: NGK insulators)

Transmission and distribution

1) Stability of transmission lines: capacity to keep the synchronism of network components and prevent the collapse of the system. When transmission lines fail they have an impact on constant energy transmissions, generators may tend to lose the synchronism. If the response to the first oscillation is not adequate all the generators lose the synchronism leading to a total decay of the system. Energy Storage Systems may be used to store or supply energy to generators to keep the synchronism

2) Voltage regulation: capacity to keep the voltage around a 5% deviation from the nominal value. Grid operators use the automatic voltage regulation to control voltage decays or transmission dips. Sudden voltage dips lead to the instability of the system. To strengthen the system new lines and transformers may be added but this is an expensive solution. Energy Storage Systems may be fast and cost-effective solutions to improve the voltage regulation supplying active power in the face of the disconnection of large loads or large voltage dips.

3) Deployment of investment on transmission: capacity to postpone the installation of new transmission lines or/and transformers. When a transmission line reaches its threshold peak is necessary to install new lines and transformers. As loads increase gradually these additional lines are underemployed in the first years. The deferred investments may involve certain savings. Modular Energy Storage Systems may be may be added as the load increases. These systems would defer the investments supplying a portion of the peak consumption.

4) Deployment of investment on distribution: capacity to postpone the installation of new distribution lines or/and transformers. This application is the same as the previous one.

Customer services

1) Customer's demand peak reduction: the storage of energy during consumption valleys to dispatch it during demand peaks may reduce the monthly peak commission of the customer and they may get better prices.

2) Uninterruptible Power Supply (UPS): the potential customers of these applications are the ones with sensitive equipments that cannot be disconnected in any moment. These system store energy during consumption valley store supply it to the critical loads when voltage dips or blackouts occur.

3) Little customers: capacity to prevent voltage deviations of few cycles (from less than a second to minutes) avoiding data or production losses for customers under 1MW.

4) Large customers: capacity to prevent voltage deviations of few cycles (from less than a second to minutes) avoiding data or production losses for customers over 1MW.

1.2. Objective of the thesis

As mentioned before the framework of this thesis is based on the new challenges of the electrical grid due to the increasing penetration of renewable energies and Distributed Generation. The use of Energy Storage Systems for grid connected applications is getting significance in recent years and it is therefore a technology that is getting an important development.

Within this framework the main objective of this thesis is to analyze the use of Energy Storage System to maximize the integration of Distributed Generation. The use of ESS is proposed here as a suitable solution for different problems related to the integration of DG.

Once the main objective of the thesis is described the partial objectives to accomplish the aim of the thesis are the followings:

- Description of different ESS technologies.
- Modeling and simulation of electrical grids with high penetration of DG.
- Analysis of the voltage and frequency regulation in electrical grids.
- Analysis of the use of ESS for Grid Support applications.
- Analysis of the use of ESS for Energy Management applications.
- Design proposal of a Hybrid ESS for Grid Support applications.

1.3. Description of the chapters

In chapter 2 different ESS technologies and their capability to respond in the face of different problems are analyzed. The most important technologies and their potential application are discussed.

The analysis of the impact of the massive integration of DG is complex. To analyze voltage and frequency stability in distribution grids with bi-directional power flows a model of electrical power system is developed and a Dynamic Power Flow simulation tool is proposed in chapter 3. Models of different generation units, loads and ESS are proposed to be used in the simulation.

In chapter 4 the most important problems related to the stability of the electrical grid are analyzed: frequency and voltage stability. The regulation of voltage and frequency in electrical grids is explained.

In chapter 5 the use of ESS is discussed as a solution for different Grid Support applications. Different solutions based on ESS are proposed for three different Grid Support applications: Voltage Regulation, restoration of large frequency deviations and Primary Frequency Regulation.

In chapter 6 the use of ESS is discussed as a solution for Energy Management applications. The use of ESS is proposed to control the power dispatch of Wind Farms.

In chapter 7 a Hybrid ESS that combines different ESS technologies is proposed as a solution for the different Grid Support applications that are discussed in this thesis.

In chapter 8 are discussed the conclusions and the future lines of the thesis. In chapter 9 the scientific publications presented during the carrying out of this thesis are listed and in chapter 10 the scientific references used in this document are listed.

Chapter 2

Energy Storage Systems

2. Energy Storage Systems

2.1. Introduction

This chapter discusses about the characteristics of the different Energy storage Systems (ESS) and their application on electricity networks management: Energy Management and Power Quality.

Figure 8 shows the different energy storage technologies depending on the rated power and the discharge times that can achieve each technology. Depending on these properties an Energy Storage technology can be used for different applications. Technologies with long discharge time (hours) can be used for energy management. A typical application is load leveling, which involves the charging of storage when energy cost is low and utilization as needed. This would also enable consumers to be grid-independent for many hours. Technologies with discharge time of seconds or minutes can be used as bridging power, supplying the needed power while changing from one power source to other. Technologies with very fast discharge time (seconds or less) and high power can be used to assure the power quality [31].

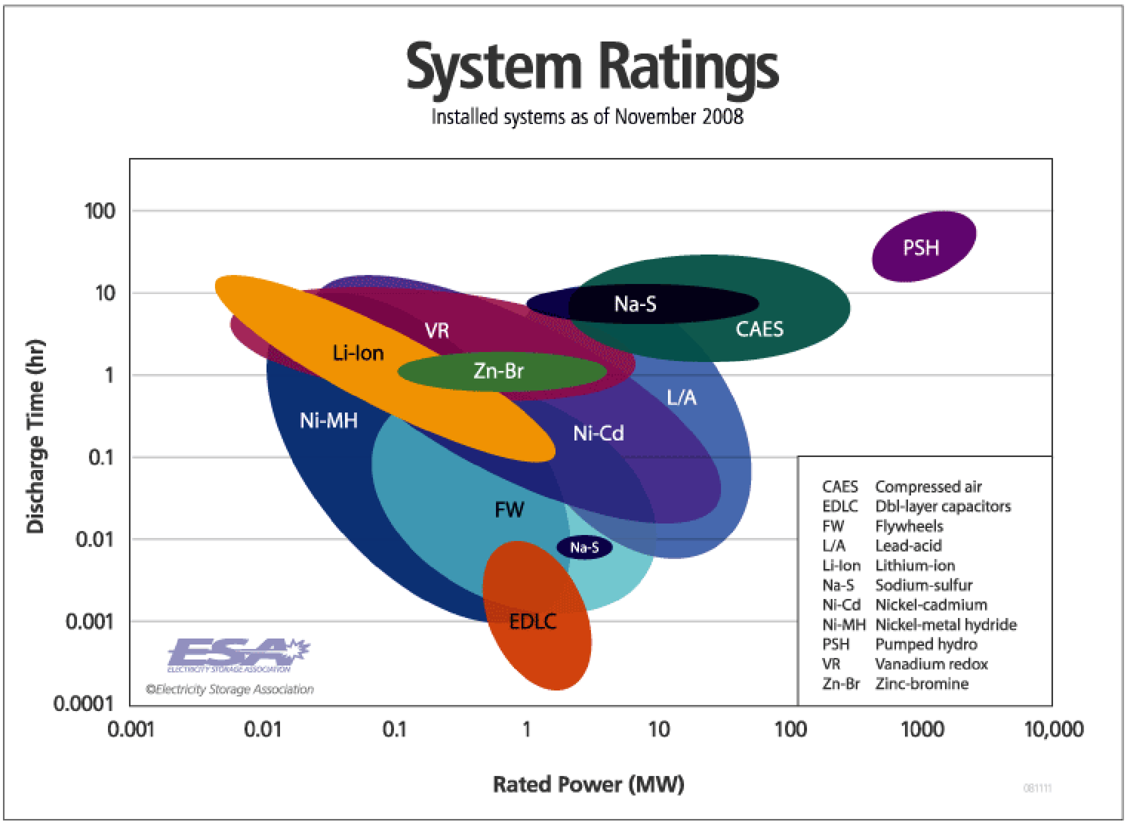


Figure 8: ESS classification depending on the power ratings, discharge time and application. Source: Electricity Storage Association (ESA)

Energy Management and Power Quality applications are interesting to improve the integration of Distributed Generation. The use of ESS for Energy Management permits a better exploitation of renewable energies adjusting the generation to demand. The use of ESS to improve the Power Quality permits a larger penetration of Distributed Generation.

2.2. Energy Storage Technologies

Different storage technologies might be used to improve the integration of Distributed Generation. CAES and Pumped Hydro Storage are normally used for large scale Energy Management. For the topic analyzed in this thesis storage technologies with rated powers between several kW and few MW are interesting. Batteries, Flywheels, Ultracaps and SMES storage technologies are focused in this chapter.

Main characteristics of different storage technologies are explained in the following subchapters.

2.2.1. Lead Acid Batteries

Lead-acid batteries are low cost and very popular for electricity storage. These batteries may be used to improve power quality, as UPS or as a reserve to make up for grid fluctuations. On the one hand it is a very mature technology, with a high performance (75-80%) and it is the battery system with the lowest initial costs. On the other hand the life cycle of these batteries is very limited and the capacity/weight ratio is very low. The wastes of these batteries are very toxic although nowadays the 90% of them is recycled.

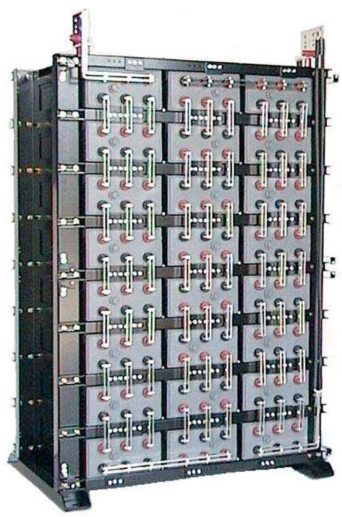


Figure 9: Lead-acid battery module

2.2.2. Ni-Cd Batteries

Nickel-Cadmium (NiCd) batteries are more expensive than lead-acid batteries and the cadmium is a very toxic heavy metal, but they have many advantages. It is a very reliable technology and they need less maintenance, they can withstand extreme working conditions and they can suffer deep discharges (around 100%) without damaging the life cycle and the efficiency of the battery. Their cycle life is much longer than lead-acid batteries (close to double) [32]. One of their drawbacks is the discharge characteristic due to the memory effect. Since their internal resistance is much smaller than lead-acid batteries the output voltage keeps constant until the stored energy is exhausted. The company ABB is going to build in Alaska the largest BESS with 20MW power and 5MWh of storage capacity, based on NiCd batteries. The main purpose of the installation is the response against faults in the supply, although it will help to the grid management in normal conditions [33].

Figure 10: Biggest BESS in the world in Fairbanks, Alaska, USA.

In recent years Nickel Metal Hydride (NiMH) batteries have gained prominence over this technology [32]. NiMH batteries compared to NiCd have longer life cycle, less pronounced memory effect, a higher energy density and they do not have cadmium.

2.2.3. High temperature Batteries

Within high temperature battery systems ZEBRA and NaS batteries are the most mature technologies. The first one is developed by the Swiss company MES-DEA and the second one is developed by the Japanese company NGK insulators. These technologies require high temperatures to maintain the electrolyte liquid. Therefore this electrolyte has to be insulated. The total disconnection of these systems would provoke the solidification of the electrolyte, losing its properties and reducing the life time of the battery.

NaS batteries

The NaS technology is composed by liquid sulfur in the positive electrode and liquid sodium in the negative electrode as active elements and separated by an electrical insulator. This technology is already implemented in 190 places, with a total installed power of 270 MW and 1600 MWh of capacity. The use of these batteries for stationary applications like load leveling or auxiliary services is expanding around the world. Many projects are carrying out in USA, Japan and Europe. This technology is designed to reduce the fluctuations between electricity demand and generation. NaS batteries have a higher energy density and efficiency, compared to conventional batteries. Due to the high temperature (250°C-350°C) that is necessary these batteries are available only for large applications. The larger is a NaS battery the more efficient is the installation. These batteries need three times less room than lead-acid batteries. Moreover they have no gas emissions, no vibration and no noises. The largest installations of this type are in Japan (Hitachi Factory 8MW 56MWh and Tohoku wind farm 30MW 216MWh) but some new projects are going to be built in US [33, 34].

Figure 11: NaS battery module

ZEBRA batteries

ZEBRA batteries work with a temperature between 270°C and 350°C, this requires a thermal protection box for each battery module. These batteries are used in applications of high capacity. It might work with high voltages up to 600V. ZEBRA batteries have a high energy density, they do not need maintenance. The cycle life of these batteries has reached 2000 cycles and MES-DEA considers that in normal operating conditions the life cycle may be considered infinite. This technology is normally used for vehicle applications but due to its high energy capacity it might be used in utility applications.

Figure 12: ZEBRA battery module

2.2.4. Flow Batteries

Flow batteries store and return energy by means of a reversible reaction between the electrolytes separated by an ion exchanger membrane, as it is shown in Figure 13.

The energy in these systems is stored in the electrolyte tanks, so the energy storage capacity depends on the electrolyte stored in the tanks. While the power output of these systems is dependent on the Power Conversion System.

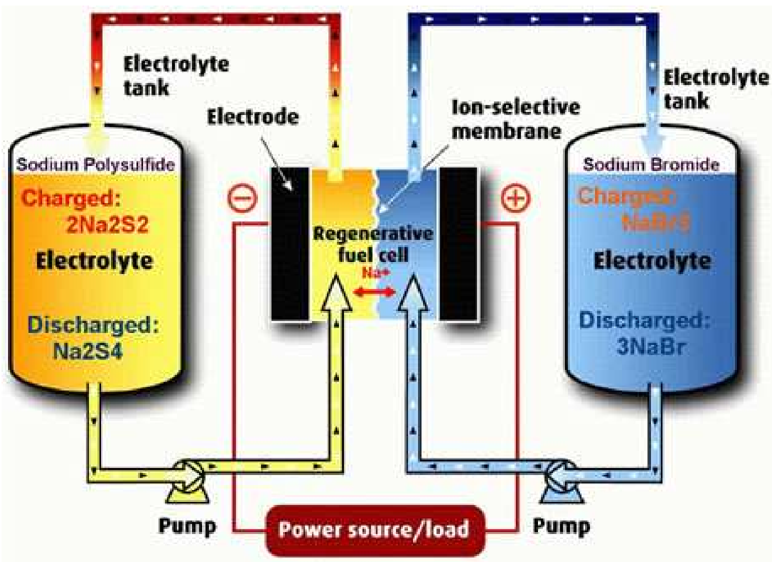


Figure 13: General configuration of flow batteries

These technologies require a large infrastructure to be installed. There are two types of commercially available flow batteries: Vanadium REDOX batteries and Zinc Bromide batteries. At the moment of redacting this thesis the only manufacturer of Vanadium REDOX batteries has already disappeared.

The efficiency of REDOX batteries might be up to 85%. This technology is used for utility applications or even for UPS. There have been used in a wide range of grid connected applications. These batteries are very efficient and their response capacity is very fast. Batteries of up to 500kW and 5MWh have been installed in Japan by Sumitomo Electric Industries, while Prudent Energy installed it for power quality applications (3MW during 1.5 seconds).

Zinc Bromide batteries have an efficiency of up to 75%. Nowadays there are three main companies that produce these batteries: ZBB Energy, Red Flow and Premium Power. Red Flow commercializes UPS applications, while ZBB and Premium are used for utility applications. These technologies have a very fast response and high storage capacity of storage and power.

2.2.5. Li-ion Batteries

The main advantages of this technology are the high energy density (300-400kWh/m^3, 130kWh/ton), the high efficiency (almost 100%), low self-discharge and the long life (around 3000 cycles with discharges of 80%) [32]. In a short time Li-ion batteries dominate the 50% of portable technology, but their development for utility applications presents several problems. The most important is the high cost. Several companies are working to reduce production costs for utility applications. The electric vehicle market is also pushing the development of these batteries. Although the main problem is the low reserve of Lithium in the world [35]

Figure 14: Large Li-ion battery facility for frequency regulation.

Within Li-ion batteries different technologies are used for utility applications: Lithium-Iron-Phosphate, Lithium-Nanophosphate, Lithium-Titanate or Lithium-Hexafluorite-Phosphate. The main difference between all these technologies is the charge/discharge profile. The technologies with high charge/discharge currents may supply high power very fast but their energy storage capacity is limited compared to NaS batteries.

2.2.6. Ultracaps

Ultracaps or Electrochemical Double Layer Capacitors (EDLC) have the capacity to store more energy than conventional capacitors and they can also supply more power than batteries. Ultracaps can absorb and supply high currents (10-1000A) and their fast response of charge and discharge permits a high performance. Since there is not any chemical transformation in the charge/discharge process their cycle life is much higher than batteries (500000-1000000 cycles). The state of charge of the Ultracaps is proportional to voltage, so it is easy to calculate. Their specific power is much higher than for batteries, although their energy density is lower [36].

Figure 15: Ultracaps Energy Storage System, Palmdale, California, USA

Due to the low energy storage capacity and the possibility to supply high power pulses Ultracaps can be used in many applications, from those where short power pulses are required to those where low power supply is needed. Using them or combining with other power sources, Ultracaps are a good solution in many system configurations and high power applications: UPS, industrial lasers, medical equipment, and power electronics for vehicles. Since the Ultracaps have a fast response and high power can be a good solution as short term (power supply during seconds or minutes) source but it cannot substitute batteries as a long term (power supply during hours) source. The combination of both technologies can be a good when it is needed a fast response together with long term energy storage [37].

2.2.7. Flywheel

The flywheels are kinetic energy storage systems. This system stores energy accelerating a high inertia rotor and supplies it back decelerating this rotor. The flywheels have a very fast response and they can supply high power peaks.

The main advantages of flywheels are the high specific power (5-10kW/kg) and energy (50-350Wh/kg), the long cycle life (around 20 years), the low maintenance costs, the high performance (95%) and the low environmental impact (there is not any toxic component). One of the main disadvantages is that since it works with a very high speed there is the risk of supplying all the energy in an uncontrolled way in case of malfunction [30]. The other main handicap is that there are so few flywheel manufacturers.

Figure 16: Flywheel cabinet.

Depending on the maximum rotational speed Flywheels are classified as low and high-speed. The border between the two systems is around 10000 rpm [32].

The main manufacturers are Pentadyne and Beacon Power. The biggest flywheel installation has been designed by Beacon Power; it will be a frequency regulation plant of 20MW and 5MWh.

2.2.8. SMES

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil that has been cryogenically cooled to a temperature below the superconducting critical temperature. The SMES system includes mainly three parts: a superconducting coil, a power conditioning system, and a cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conversion system (PCS) uses an inverter/converter to transform AC power to direct current or convert DC back to AC power. The inverter/rectifier accounts for some energy loss in each direction [38]. The SMES loses the least amount of energy in storage process compared to other methods of storing energy. SMES systems are highly efficient; the round trip efficiency is greater than 95%. Even so, the energy requirements of refrigeration and the high cost of superconducting wire reduce this efficiency.

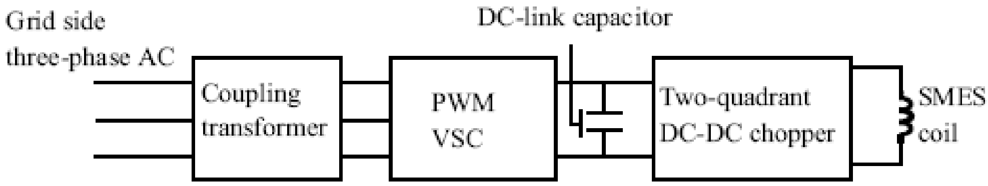


Figure 17: Basic Components of a SMES control system.

A Superconducting Magnetic Energy Storage (SMES) system, designed to improve the power quality for critical loads, provides carryover energy during voltage sags and momentary power outages. The system stores energy in a superconducting coil immersed in liquid helium [39]. The most significant medium-scale SMES project is a 500 kWh energy storage facility in Anchorage, Alaska. It is used as spinning reserve. It can dispatch 30 MW for one minute [37].

Figure 18: 2MJ SMES prototype.

2.3. Chapter conclusions

The use of ESS is changing from UPS applications to a wider application range, grid connected applications are analyzed in this case. In this chapter the best technologies for grid connected ESSs have been analyzed. New battery technologies like Li-ion, NaS or flow batteries have the best characteristics for grid connected energy applications, but lead acid are still the most used batteries, due to their low cost. The industry tends to use Li-ion batteries to substitute lead acid batteries for small applications and this tendency is also happening for grid connected applications, this technology may be used for Power Quality applications but also for Energy Management applications. NaS batteries are used for large Energy Management applications with several MW for several hours. For Power Quality applications Ultracaps, Flywheels and SMES may be used, nowadays Ultracaps are the technology that has reached more development with several manufacturers working with this technology.

TABLE 1
MAIN CHARACTERISTICS OF DIFFERENT BESS TECHNOLOGIES

		Li-ion	NaS	ZEBRA	REDOX	Zn-Br	Pb-acid
Charge		2C-5C	0,17C	3C-3,5C	0,25C-0,28C	0,035C-0,66C	1,5C
Discharge		10C-30C	0,17C	0,5C-1C	0,25C-0,5C	0,18C-0,67C	0,1C-0,2C
Density	Wh/kg	65-105	70	101-119	4,5	27,7-64	17,5-32,4
	Wh/l	80-22		154-183	15-25	9,5-16,3	31,9-110
	W/kg	650-850	11,6	170	80-150	11,5-37,5	22,5-55,4
	W/l	800-1750		261		2,9-11,2	71,6-195
Life Cycle		2000-3000 (80% DOD)	2500 (100% DOD)	2000-infinite (100% DOD)	2000->10000 (100% DOD)	2000-infinite (100% DOD)	1000-1500 (80% DOD)

TABLE 2
MAIN CHARACTERISTICS OF FLYWHEELS AND ULTRACAPS

	Flywheel	Ultracaps
Rated power	100-200kW	25-250kW
Energy	0,7-25kWh	92-530kWh
Life Cycle	infinite cycles	1000000 cycles
Response time	< 4 seconds	instantaneous

In Table 1 principal characteristics of different battery technologies are shown. Faster response technologies like Flywheels and Ultracaps are compared in Table 2. Characteristics of SMES are not shown because this technology is not still commercially available.

In both tables main characteristics of single storage modules are shown. With series and parallel connection of different modules different energy and power configurations may be obtained.

For an Energy Storage System that is able to work for Power Quality and Energy Management applications some Li-ion technologies may be used due to their large discharge currents (up to 10C). Depending on the range of response time, power or energy this solution may be insufficient and other technologies should be used. In this thesis a Hybrid ESS that combines batteries and Ultracaps is proposed.

Table 3 shows the main advantages and disadvantages of different ESS, as well as their feasibility for power or energy applications.

TABLE 3
MAIN PROPERTIES AND APPLICATIONS OF DIFFERENT ESS

Storage Technology	Main Advantages	Disadvantages	Power Application	Energy Application
Flow batteries	High capacity, Independent power and energy rating	Low Energy Density	Reasonable	Fully capable and reasonable
NaS	High Power and Energy densities, high efficiency	Production cost, safety concerns	Not reasonable	Fully capable and reasonable
Ni-Cd	High Power and Energy densities, efficiency	Cadmium is a heavy metal	Fully capable and reasonable	Reasonable
Lead-Acid	Low capital cost	Limited Cycle Life when deeply discharged	Fully capable and reasonable	Feasible but not quite economical
Flywheels	High Power	Low Energy Density	Fully capable and reasonable	Feasible but not quite practical
SMES	High Power	Low Energy Density, High production cost	Fully capable and reasonable	Not feasible
Ultracaps	Long Cycle Life, High Efficiency	Low Energy Density	Fully capable and reasonable	Not feasible
Pumped Hydro	High Capacity, Low cost	Special site requirement	Not feasible	Fully capable and reasonable
CAES	High Capacity, Low cost	Special site requirement	Not feasible	Fully capable and reasonable
Li-ion	High Power and Energy densities, high efficiency	High production cost	Fully capable and reasonable	Reasonable

Chapter 3

Modeling and simulation of the electrical grid

3. Modeling and simulation of the electrical grid

3.1. Introduction

In order to analyze the contribution of Energy Storage Systems in electrical grids, a power system with different generators, lines and Energy Storage Systems should be analyzed. The aim of this chapter is the development of a power system model and the simulation tool to analyze its behavior.

The electrical grid is simulated using a Power Flow calculation method. The information about electrical lines and the different generation and consumption units is used to calculate the Power Flow in the grid. A simulation tool based on Matlab-Simulink is proposed in this chapter. Any power system might be modeled in this simulation tool based on the dynamic calculation of the Power Flow in the power system.

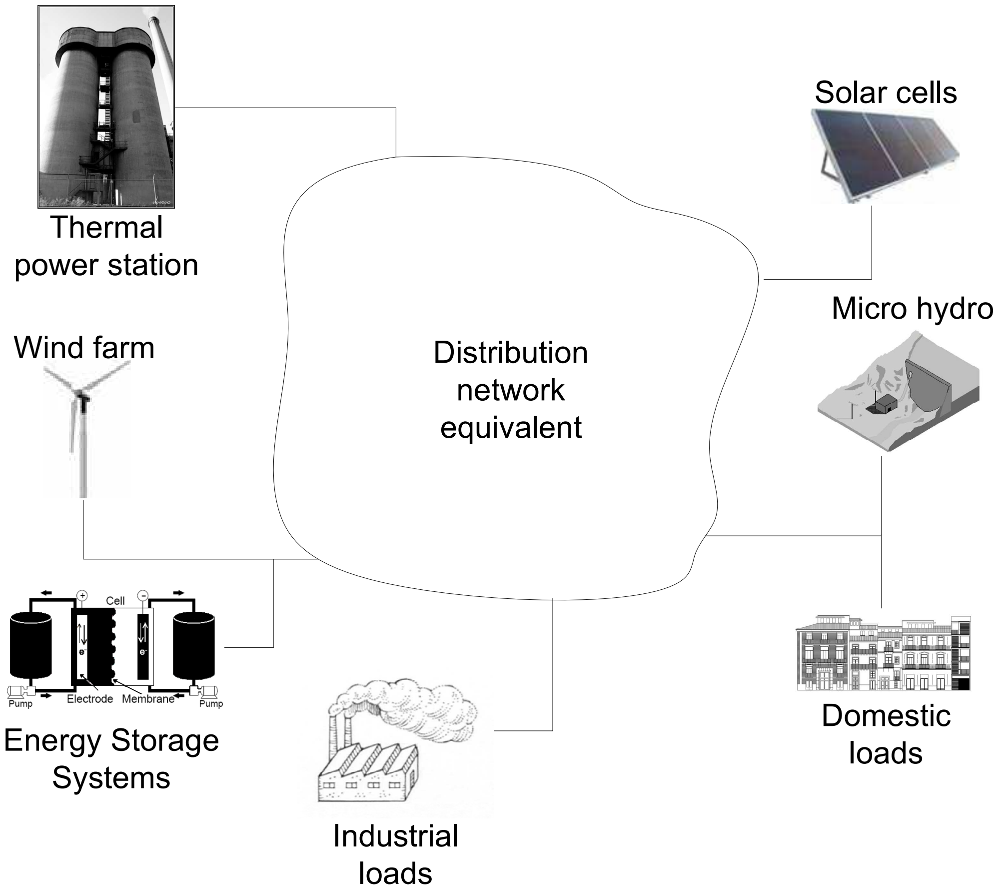


Figure 19: Distributed electrical grid model.

Simplified models of different generation centers (such as wind farms, diesel gensets, reheat power stations...) are modeled to be used in the proposed simulation tool. This simulation tool will give the possibility to analyze the voltage and frequency stability simultaneously.

3.2. Simulation tool

3.2.1. Power Flow calculation

The Power Flow analysis involves the calculation of power flows and voltages of a transmission network for specified terminal or bus conditions. Such calculations are required for the analysis of steady-state as well as dynamic performance of power systems. In a complex power system like a distribution network the calculation of the currents and voltages through the grid is very complex. The Power Flow calculation is a numerical method that permits the calculation of these currents and voltages based on the power injections in the nodes of the system [13].

To calculate the Power Flow is necessary to know the values of the lines of the power system and the power injected in each node of the system. From these values the Power Flow calculation method calculated the voltages and the currents in all the nodes and after some iteration Power Flow is solved. As any numerical method the Power Flow calculations needs a good initialization, otherwise the method might diverge.

The power system is assumed to be balanced; this allows a single-phase representation of the system. In Power Flow analysis there are associated four quantities with each node: active power P, reactive power Q, voltage magnitude V and voltage angle θ.

Commonly the following types of buses (nodes) are represented and at each node two the above four quantities are specified:

Voltage controlled (PV) bus: Active power and voltage magnitude are specified. In addition, limits to the reactive power are specified depending on the characteristics of the individual devices. Examples are buses with generators, synchronous condensers and static var compensators (STATCOM).

PQ bus: Active and reactive power are specified. Loads and generation units might be represented with this type of nodes.

Slack bus: Voltage magnitude and phase angle are specified. Because the power losses in the system are not known a priori, at least one bus must have unspecified P and Q. Thus the slack bus is the only bus with known voltage.

The relationships between network bus (node) voltages and currents may be represented by either loop equations or node equations. Node equations are normally preferred because the number of independent node equations is smaller than the number of independent loop equations. The network equations in terms of node admittance matrix can be written as follows:

$$\begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \\ \cdots \\ \tilde{I}_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & \cdots & Y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ Y_{n1} & Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \cdot \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \\ \cdots \\ \tilde{V}_n \end{bmatrix}$$

where

n is the total number of nodes

Y_{ii} is the self admittance of node i, sum of all the admittances terminating at node i.

Y_{ij} is mutual admittance between nodes i and j, negative of the sum of all admittances between nodes i and j

$\tilde{V}_i$ is the phasor voltage to ground at node i

$\tilde{I}_i$ is the phasor current flowing into the network at node i

The admittance matrix is based on the values of all the line admittances of the power system. Using the admittances the calculation of the matrix is much easier compared to the impedances [13].

These equations would be linear if the current injections $\tilde{I}$ where known. However, in practice, the current injections are not known for most nodes. The current at any node k is related to P, Q and $\tilde{V}$ as follows:

$$\tilde{I}_k = \frac{P_k + jQ_k}{\tilde{V}_k^*} \tag{3. 1}$$

For the PQ nodes, P and Q are specified; and for PV nodes, P and the voltage magnitude are specified. For slack nodes the relationship between P, Q, $\tilde{V}$ and $\tilde{I}$ are defined by the characteristics of the devices connected to the nodes. Clearly the boundary conditions imposed by the different types of nodes make the problem nonlinear and therefore Power Flow equations are solved iteratively using techniques such as Gauss-Seidel, Newton-Raphson or Bacward-Forward sweep methods, for example [13].

3.2.2. Dynamic Power Flow

At this point it is proposed the dynamic simulation of a power system using the dynamic Power Flow calculation. The Power Flow calculation is done every simulation step in this way the dynamic behavior of the power system is calculated. The inputs of the simulation tool are the power injections in each node.

The simulation method developed in this thesis consists of a function developed in Matlab Simulink to calculate the Power Flow by means of a Backward Forward Sweep numerical method. This function is called from a Simulink model, which contains the models of the different generation units and the load demand in the power system. All the generators and loads are considered as PQ load, but one node is considered as slack node.

With the Power Flow calculation instantaneous values of voltages and currents are obtained. The frequency variation is obtained calculating the power balance in the system depending on the inertia of the different generators.

The inertial energy stored in the shaft of an electrical machine supplies the instantaneous power difference between the mechanical power generation and the electrical power need, as equation (3. 1) represents. In this equation P_{elec} is the total electrical power need, P_{mec} is the total mechanical power generation, J_T is the total inertia of the power system and α is the angular acceleration of the power system. The angular acceleration of the power system is a parameter that defines the variation of the grid frequency in the power system.

$$P_{elec} = P_{mec} - J_T \cdot \alpha \tag{3. 2}$$

The total inertial reserve of a power system is represented by the equivalent inertia of the system, which is the sum of all the inertias of all the generators connected to the system.

$$J_T = J_1 + J_2 + ... + J_N \tag{3. 3}$$

The behavior of a power system in the face of generation losses or load variations may be defined by the following steps until restoring the frequency to its nominal value [13].

Stage 1: immediately after the disturbance generators output change in approximately inverse proportion to the reactance between the generator and the point where generation or load is lost.

Stage 2: between 0.5 and 2 seconds after the disturbance the generators accelerate or decelerate due to imbalance between the mechanical power input and electrical power output in proportion to their inertia.

Stage 3: between 2 and 20 seconds following the disturbance the speed governors respond and change the turbine outputs. At the end of this stage generators share the power change in proportion to their capacity. Speed droop governors and frequency regulation are more deeply explained in the next chapter.

Stage 4: tens of minutes after the disturbance the Automatic Generation Control (AGC) restores the frequency to its nominal value. This is also explained in the next chapter.

For the Dynamic Power Flow Simulation tool proposed at this point stage 1 is neglected in order to make calculations easier.

3.3. System modeling

The information about the different lines and connection points of the electrical grid are stored in an archive that the Power Flow calculation function calls to simulate the power system.

The Power Flow simulation tool has as inputs the models of the different generators and loads. Load might be modeled as a variable value of active and reactive power that follow a load demand curve.

Generation units are modeled in order to obtain their dynamic response in order to analyze frequency and voltage regulation issues. Different generation units should be modeled to be a PQ node for the simulation tool. Basic models of wind farms, diesel generators, reheat steam turbine, hydro turbines and Energy Storage Systems are shown in this chapter.

3.3.1. Wind farm

Wind Farms as all the power sources are considered as PQ nodes with variable active and reactive power. The model of wind farm consists of an aerodynamic model that transforms the wind speed value to Mechanical torque, this mechanical torque and the grid voltage and frequency are the inputs of the electrical machine model. In this thesis an induction machine has been chosen to model the wind turbine.

The wind profiles for the different simulations are defined by real wind measurements of 10 minutes mean values and standard deviation. The typical deviation and maximum deviation of the same measured wind are used in order to create the wind profile for the wind farm. The temporal wind profile series are created filtering these mean values and adding frequency components and white noise based on the standard deviation [40, 41]. The frequency components are considered for three blades wind turbines.

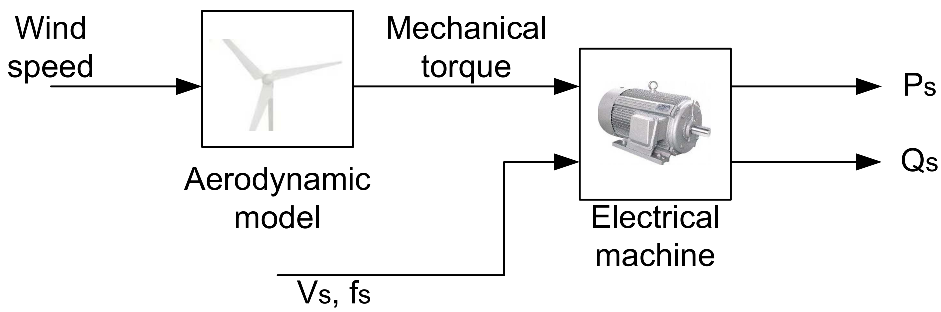


Figure 20: Wind Farm model diagram.

The electrical machine model of the wind farm is based on the steady state equivalent scheme of the induction machine:

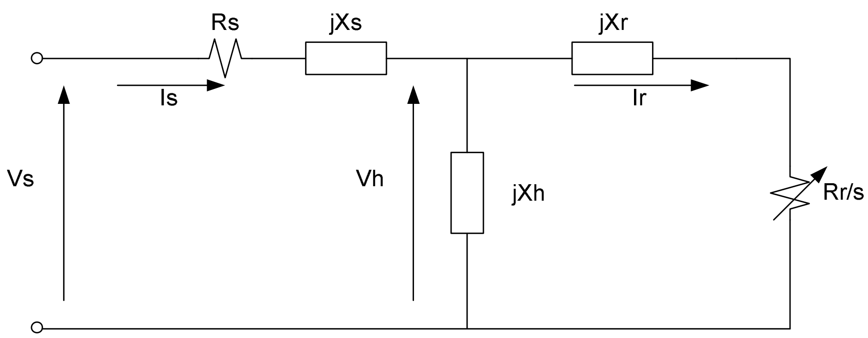


Figure 21: Equivalent circuit of the electrical machine

The inputs of this model are the input voltage and the mechanical torque. The mechanical torque is defined by the aerodynamic model of the wind turbine. A simplified model transforms wind speed values into mechanical power values, dividing this power by the angular speed of the electrical is obtained the mechanical torque.

The active and reactive power behavior of the electrical machine may be defined by the following equations:

$$T_{em} = \frac{P_{mec}}{\Omega_m} \tag{3. 4}$$

$$P_s = 3 \cdot |V_s| \cdot |I_s| \cdot \cos(ang(V_s) - ang(I_s)) \tag{3. 5}$$

$$Q_s = 3 \cdot |V_s| \cdot |I_s| \cdot \sin(ang(V_s) - ang(I_s)) \tag{3. 6}$$

From the previous equations the active and reactive power of the electrical machine may be represented by the following block diagram:

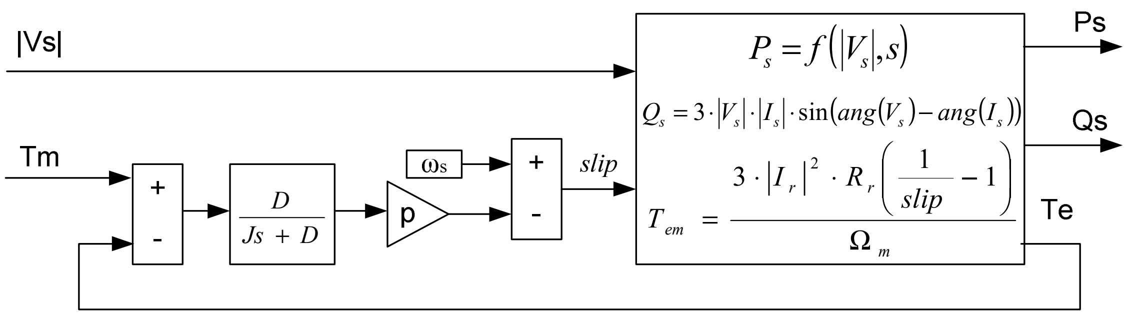


Figure 22: Block diagram of the induction electrical machine.

3.3.2. Diesel generator

Diesel generators have a fast dynamic response compared to steam or hydro turbines and they are able to adapt their generation in few seconds. The diesel prime-mover is known to have two principal system frequencies, of which one corresponds to the valve actuator, and the other to the system inertia [37].

In terms of an electrical system, a diesel generator may be represented as a prime mover and a generator. Ideally, the prime mover is capable of supplying any power demand up to rated power at constant frequency, and the synchronous generator connected to it must be able to keep the voltage constant at any load condition, The diesel engine keeps the frequency constant by maintaining the rotor speed constant via its governor [38].

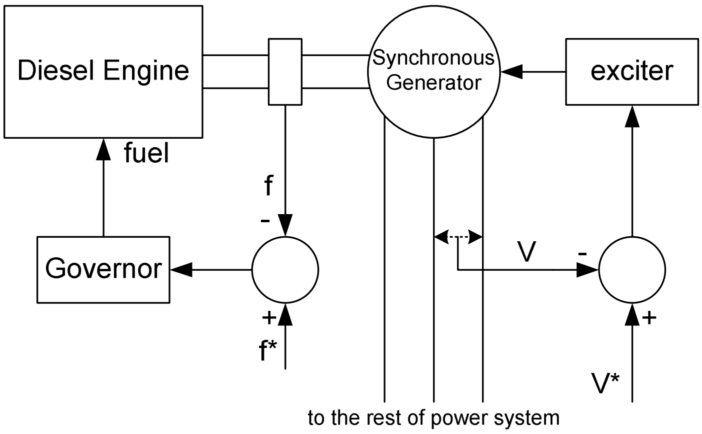


Figure 22: Diesel generator control block diagram.

The system has been modeled in two parts. The exciter has been modeled as a voltage/reactive droop characteristic, the generator injects the necessary reactive power to maintain the voltage at nominal value. For the prime mover and the active power generation the system has been modeled as shown in Figure 23. The system consists of a governor with a frequency/active power droop characteristic that creates the reference value for the actuator of diesel valve which modeled as transfer function with several time constants and the delay of the diesel engine.

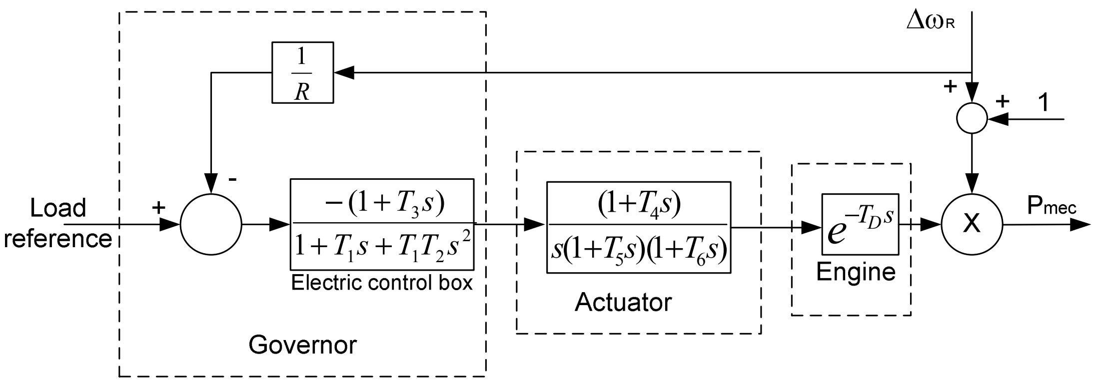


Figure 23: model of diesel generators

The load reference will be given by the secondary frequency regulation. Frequency and voltage regulation issues are widely explained in the next chapter.

3.3.3. Reheat steam turbine

A steam turbine converts stored energy of high pressure and high temperature steam into rotating energy, which is in turn converted in electrical energy by the generator. The heat source for the boiler supplying the steam may be a nuclear reactor or a furnace fired by fossil fuel.

A wide variety of steam turbine types exist. Most involve reheat and may be tandem or cross compound in configuration. The tandem compound reheat type turbine is the most common and is shown in Figure 24.

To model a steam turbine it is necessary to determine the time constant of a steam vessel. The continuity equation for a vessel is:

$$\frac{dW}{dt} = Q_{in} - Q_{out} = V\frac{d\rho}{dt} \qquad (3.7)$$

where W = weight of steam in the vessel (kg)

Q = steam mass flow rate (kg/s)

V = volume of vessel (m^3)

ρ = density of steam (kg/m^3)

t = time (s)

Assuming the flow out of the vessel to be proportional to pressure in the vessel,

$$Q_{out} = \frac{Q_0}{P_0}\Pr e \qquad (3.8)$$

where Pre = pressure of steam in the vessel (kPa)

Pre_0 = rated pressure

Q_0 = rated flow out of vessel

With constant temperature in the vessel,

$$\frac{d\rho}{dt} = \frac{dP}{dt}\frac{\partial \rho}{\partial \mathrm{Pr}e} \quad (3.\ 9)$$

$$Q_{in} - Q_{out} = V\frac{\partial \rho}{\partial \mathrm{Pr}e}\frac{d\,\mathrm{Pr}e}{dt} = V\frac{\partial \rho}{\partial \mathrm{Pr}e}\frac{\mathrm{Pr}e_0}{Q_0}\frac{dQ_{out}}{dt} = T_v\frac{dQ_{out}}{dt} \quad (3.\ 10)$$

where $\frac{\partial \rho}{\partial \mathrm{Pr}e}$ = the change in density of steam with respect to pressure

In Laplace form:

$$\frac{Q_{out}}{Q_{in}} = \frac{1}{1+T_v s} \quad (3.\ 11)$$

Which represents the transfer function of the steam vessel and T_v is its time constant. The turbine torque is proportional to the steam flow rate, thus the time constant of the reheater (T_{RH}) is the time constant of the steam vessel.

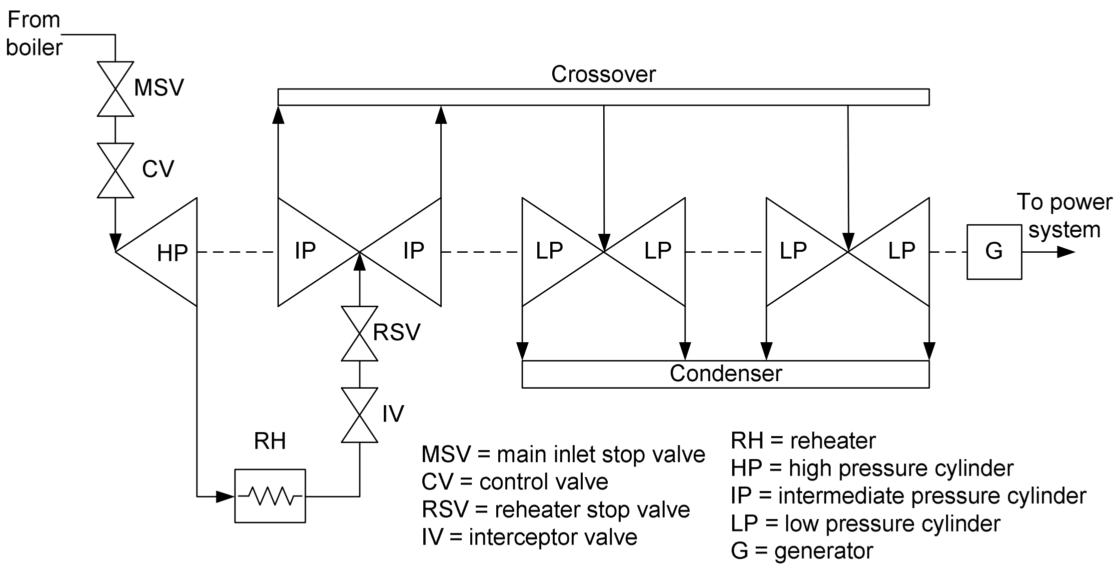
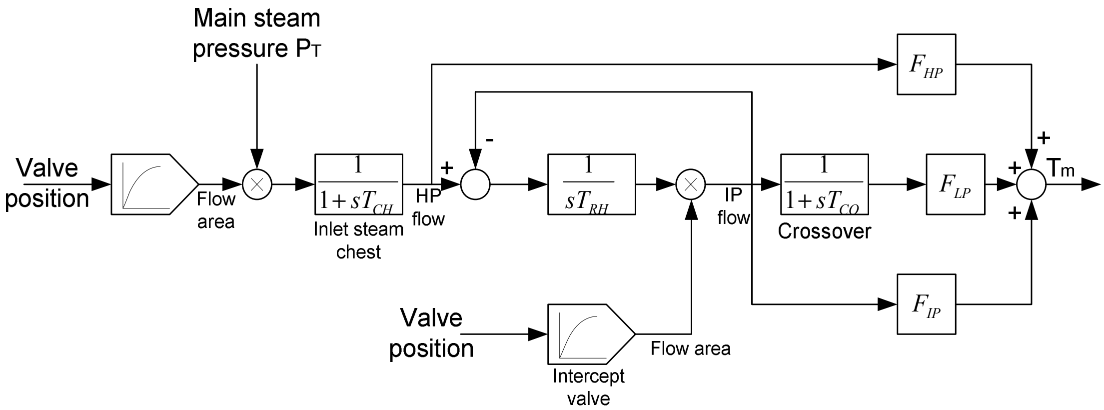


Figure 24: Common model of a single reheat steam turbine

Figure 25 shows the block diagram of the tandem-compound reheat turbine. The model accounts for the effects of inlet steam chest, reheater and the nonlinear characteristics of the control and intercept valves.



T_{CH} = time constant of main inlet volumes and steam chest
T_{RH} = time constant of reheater
T_{CO} = time constant of crossover piping and LP inlet volumes
T_m = total turbine torque in per unit of maximum turbine power
F_{HP}, F_{IP}, F_{LP} = fraction of total turbine power generated by HP, IP, LP section

Figure 25: Block diagram of the tandem compound reheat turbine.

An approximated model of the turbine relating perturbed values of the turbine torque (ΔT_m) and control valve position (ΔV_{CV}) may be written as follows:

$$\frac{\Delta T_m}{\Delta V_{CV}} = \frac{F_{HP}}{1+sT_{CH}} + \frac{1-F_{HP}}{(1+sT_{CH})(1+sT_{RH})} = \frac{1+F_{HP}T_{RH}s}{(1+T_{CH}s)(1+T_{RH}s)} \tag{3. 12}$$

In writing the above transfer function, it is assumed that T_{CO} is negligible in comparison with T_{RH} and the control valve characteristic is assumed to be linear.

For reheat steam turbines like diesel generators the valve position is given by the speed governor which controls the output voltage reference depending on the grid frequency. The relation between turbine torque and active power is proportional and the reactive power responds also to a voltage/reactive power droop characteristic.

Governors for reheat steam turbines

The steam turbine governor system consists of the speed governor, the servo machine, and the turbine [42]. In Figure 26 is shown the block diagram that defines the governing system of a steam turbine. The servo-mechanism is the responsible for opening or closing the valve gate. The digital electrohydraulic (DEH) control system uses a digital controller, which is interfaced with the turbine valve actuators (servo-mechanism) through an analogue hybrid section. For the realization of Automatic Generation Control (AGC) control relies on the coordinated control systems (CCS). For generators that do not participate in secondary frequency regulation the speed governor is composed only by the DEH, for secondary regulation is added the CCS control action.

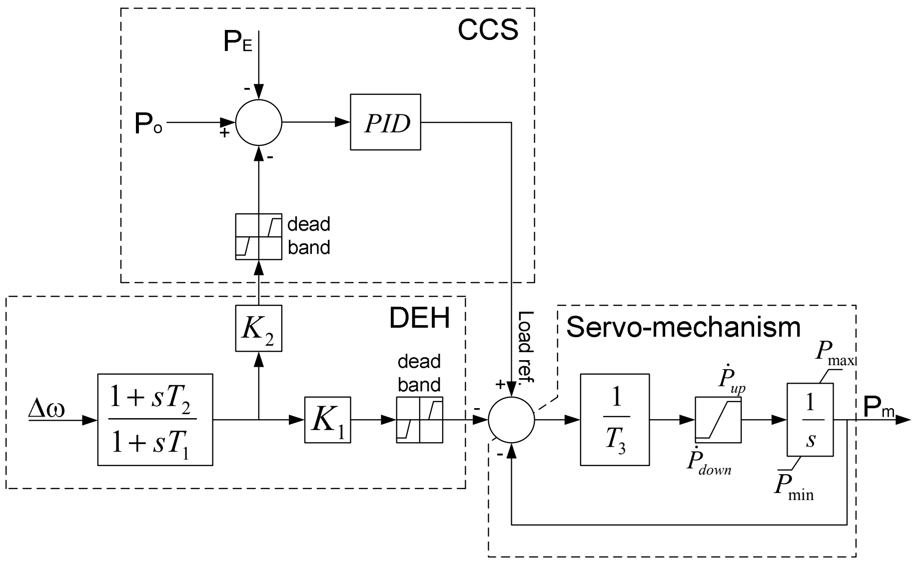


Figure 26: Block diagram of Steam Turbine governor.

T_3 is the servomotor time constant, T_1 and T_2 are the time constant values for phase correction transfer function, K_1 is the gain for the speed droop characteristic and K_2 is the gain to convert speed values to power. A more detailed model of reheat steam turbines is given in [43], from where the parameters to simulate the system were taken.

3.3.4. Hydro turbine

The performance of a hydraulic turbine is influenced by the characteristics of the water column feeding the turbine; these include the effects of water inertia, water compressibility and pipe wall elasticity in the penstock. The effect of water inertia is to cause changes in turbine flow to lag behind changes in turbine gate opening. The effect of elasticity is to cause travelling waves of pressure and flow in the pipe; this phenomenon is commonly referred to as “water hammer”.

The essential elements of the hydraulic plant are depicted in Figure 27.

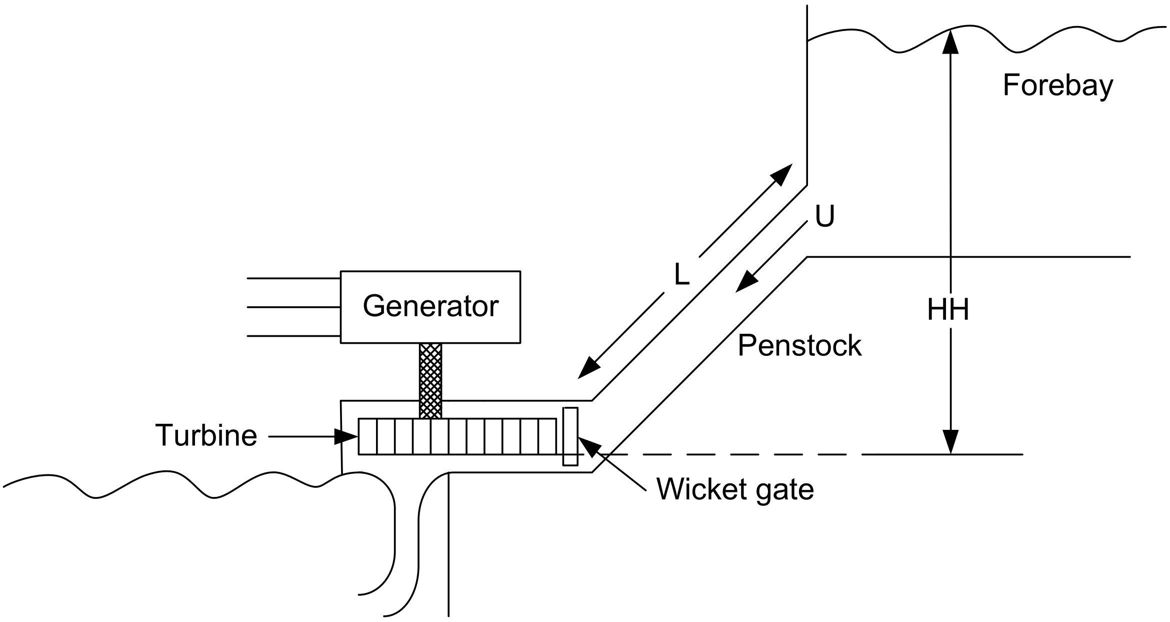


Figure 27: Schematic of a hydroelectric plant

The turbine and penstock characteristics are determined by three basic equations:

a) Velocity of water in the penstock.

$$U = K_u \cdot G \cdot \sqrt{HH} \tag{3. 13}$$

where U = water velocity
G = gate position
HH = hydraulic head at gate
K_u = a constant of proportionality
In steady state operating values:

$$\Delta\overline{U} = \frac{1}{2}\Delta\overline{HH} + \Delta\overline{G} \tag{3. 14}$$

b) Turbine mechanical power.

$$P_m = K_p \cdot HH \cdot U \tag{3. 15}$$

In steady state operating values:

$$\Delta\overline{P}_m = \Delta\overline{HH} + \Delta\overline{U} = \frac{3}{2}\Delta\overline{HH} + \Delta\overline{G} \tag{3. 16}$$

c) Acceleration of water column.

$$(\rho LA)\frac{d\Delta U}{dt} = -A(\rho \cdot a_g)\Delta HH \tag{3. 17}$$

where L = length of conduit

A = pipe area

ρ = water mass density

a_g = a constant of proportionality

ρLA = mass of water in the conduit

$\rho a_g \Delta H$ = incremental change in pressure at turbine gate

From this equation:

$$T_w \frac{d\Delta \overline{U}}{dt} = -\overline{HH} \tag{3. 18}$$

where $T_w = \dfrac{LU_0}{a_g HH_0}$

T_w is referred to as the water starting time. It represents the time required for a head HH_0 to accelerate the water in the penstock from standstill to the velocity U_0

Working out these three basic equations is obtained the classical transfer function of hydraulic turbine. For an ideal lossless turbine can be used to model hydro turbines:

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - T_W s}{1 + \frac{1}{2} T_W s} \tag{3. 19}$$

Further explanations about nonlinear models and detailed hydraulic system are given in [13].

Governors for hydraulic turbines

For a hydro turbine the typical governor with simple steady-state droop characteristic would be unsatisfactory. Hydro turbines have a peculiar response due to water inertia: a change in gate position produces an initial turbine power change which is opposite to that sought. For stable control performance, a large transient droop with a long resetting time is required. This is accomplished by the provision of a rate feedback or transient gain reduction compensation as shown in Figure 28.

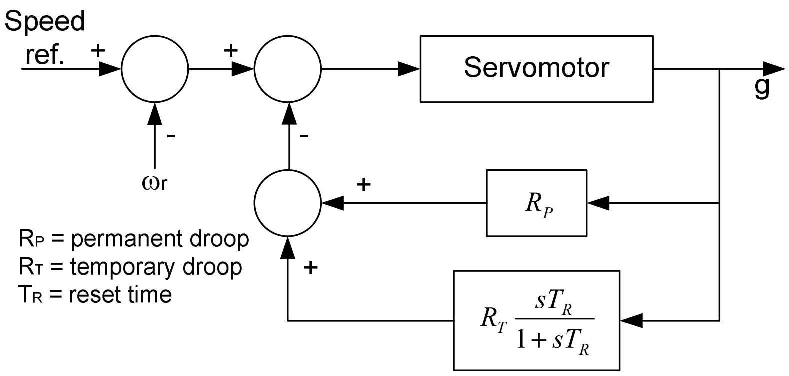


Figure 28: Governor with transient droop compensation.

The transfer function of a hydro turbine governor is defined by the servomotor transfer functions: and the transient droop compensation, being T_G the time constant of the governor:

$$\frac{\Delta G}{\Delta \omega} = \frac{1}{1+sT_g} \cdot \frac{1+T_R s}{1+(R_T+R_P)T_R s} \tag{3. 20}$$

3.3.5. Energy Storage System

For dynamic Power Flow simulations the Energy storage systems may be considered as controllable PQ nodes. The P and Q values are considered independent form each other. The active power depends on the characteristics of the storage technology while the reactive power depends on the bus capacitor. Very simple models are used for the storage technologies.

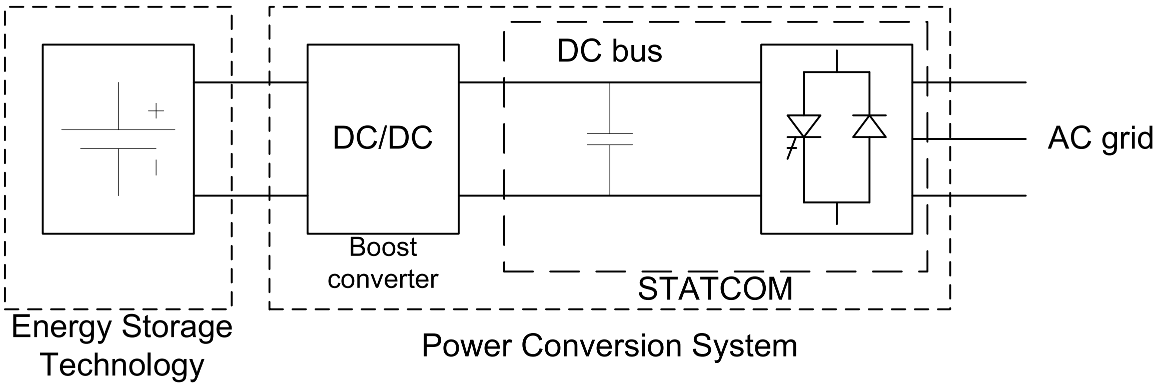


Figure 29: STATCOM+Energy Storage System model.

The grid inverter is a STATCOM which is modeled by a very fast time constant dependent on the commuting time of the modulation. The bus capacitor size will limit the maximum output reactive power and the time constant that defines the response of this energy. For the active power supply three characteristics are considered the energy stored, the maximum power output and the maximum power gradient.

3.4. Conclusions

A simple simulation tool to analyze large electrical grids has been described in this chapter. Using the dynamic calculation of a power flow the voltage and frequency behavior of a grid with many generators and loads may be analyzed with a small error using the simple models proposed in this chapter.

Chapter 4

Operation of the electrical grid

4. Operation of the electrical grid

4.1. Introduction

The most important parameters for the stability of a power systems are the voltage and frequency stability as explained in the introduction. Once defined in the previous chapter the electrical grid model and the simulation tool, this chapter will analyze the voltage and frequency control for a good performance of any electrical grid.

The control of these two parameters will be analyzed in order to show in the following chapters the contribution of ESS to control these parameters. In principle, the massive integration of renewable energies will reduce the voltage and frequency stability of the power systems, in large power systems this is not a problem yet, although stability problems have a larger effect in islands and small power systems.

4.2. Voltage regulation

Voltage stability is the ability of a power system to maintain steady acceptable voltage at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a progressive and uncontrollable drop in voltage happens [13]. The main factor causing voltage instability is the inability of the power system to maintain a proper balance of reactive power throughout the system.

Voltage stability can be classified into small disturbance voltage stability when it is concerned with a system's ability to control voltages following small perturbations such as small changes in loads, or large disturbance voltage stability when it is concerned with a system's ability to control voltages following large disturbances such as transmission system faults [44].

Traditionally in voltage regulation the most important control elements for reactive power compensation are the synchronous generators, the synchronous compensators and the capacitor banks. The use of power electronics permit very fast responses using the applications known as FACTS.

On-load Tap Changers (OLTC) are used to control the voltage in MV networks, by shifting phase angle and adjusting voltage magnitude[45].

Voltage regulation in electrical grid is done in different levels. The primary regulation acts automatically in few seconds to control the voltage in each node. The secondary regulation controls automatically the voltage in the pilot nodes every several seconds. The tertiary regulation is a combined control of voltage and frequency. The aim of the tertiary control is to optimize the load/generation balance. This control is slower than the secondary regulation of voltage and frequency and it sets the reference values for the secondary regulation in both cases [46].

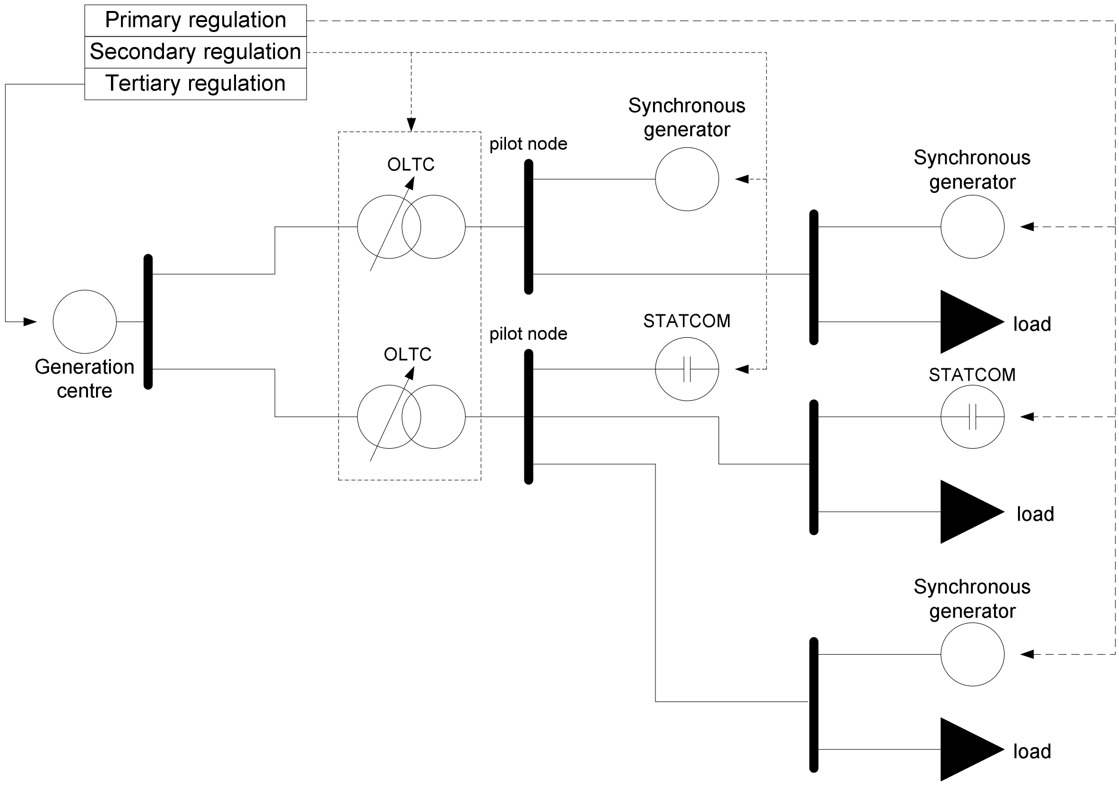


Figure 30Voltage Regulation scheme.

4.2.1. Primary voltage regulation

Consider a simple feeder, with equivalent short circuit impedance and a certain power transfer, as depicted in Figure 31.

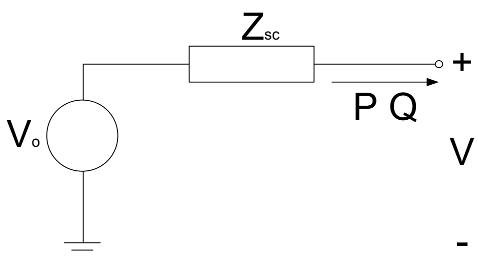


Figure 31: A simple feeder for illustration of voltage stability phenomenon

Considering a constant injection of power into the network and defining the reference system in such a manner that the grid voltage has an angle of 0, the voltage at the point of common coupling can be calculated by solving (4. 1) with respect to V.

$$V - V_0 = Z_{sc} \cdot I^* = Z_{sc} \cdot \frac{S^*}{V^*} = Z_{sc} \cdot \frac{P - jQ}{V^*} = (R + jX) \cdot \frac{P - jQ}{V^*} \quad (4.\ 1)$$

Assuming V_0 real and rewriting equation (4. 1):

$$V^* V - V^* V_0 = (R + jX) \cdot (P - jQ) \quad (4.\ 2)$$

Considering the real imaginary parts of the voltage:

$$V = V_R + jV_I$$

$$V_R^{\ 2} + V_I^{\ 2} - (V_R - jV_I)V_0 = (R + jX) \cdot (P - jQ) \quad (4.\ 3)$$

Dividing in two equations:

$$V_R^{\ 2} + V_I^{\ 2} - V_R V_0 - RP - XQ = 0$$

$$V_I V_0 = XP - RQ \quad (4.\ 4)$$

To solve these equations:

$$V_I = \frac{XP - RQ}{V_0}$$

$$V_R^{\ 2} - V_0 \cdot V_R + \left(\frac{XP - RQ}{V_0}\right)^2 - (RP + XQ) = 0 \quad (4.\ 5)$$

The real part of the voltage in the node can be defined as:

$$V_R = \frac{1}{2}\left[V_0 \pm \sqrt{V_0^{\ 2} - 4\left(\left(\frac{XP - RQ}{V_0}\right)^2 - (RP + XQ)\right)}\right] \quad (4.\ 6)$$

In p.u. the grid voltage can be considered as $V_0 = 1\angle 0^{\circ}\ p.u.$ so the equation (4. 6) can be rewritten as:

$$V_R = \frac{1}{2}\left[1 \pm \sqrt{1 - 4\left(\left(\frac{XP - RQ}{V_0}\right)^2 - (RP + XQ)\right)}\right] \tag{4. 7}$$

From the previous statements it is defined the necessary reactive power compensation in order to maintain the voltage stability in one node. In Figure 32 this relationship is shown for an active power injection of 1 p.u., a short circuit reactance of 0.6 p.u. and X/R relations of 5 and 10. This graph shows how the voltage may be controlled by the reactive power compensation.

The primary regulation is an automatic control that acts on a single node of the power system to maintain the voltage constant. Its response time is around seconds. The generator that controls the voltage in each node is based on local information without the view of the whole system. The reactive power compensation is done in each node.

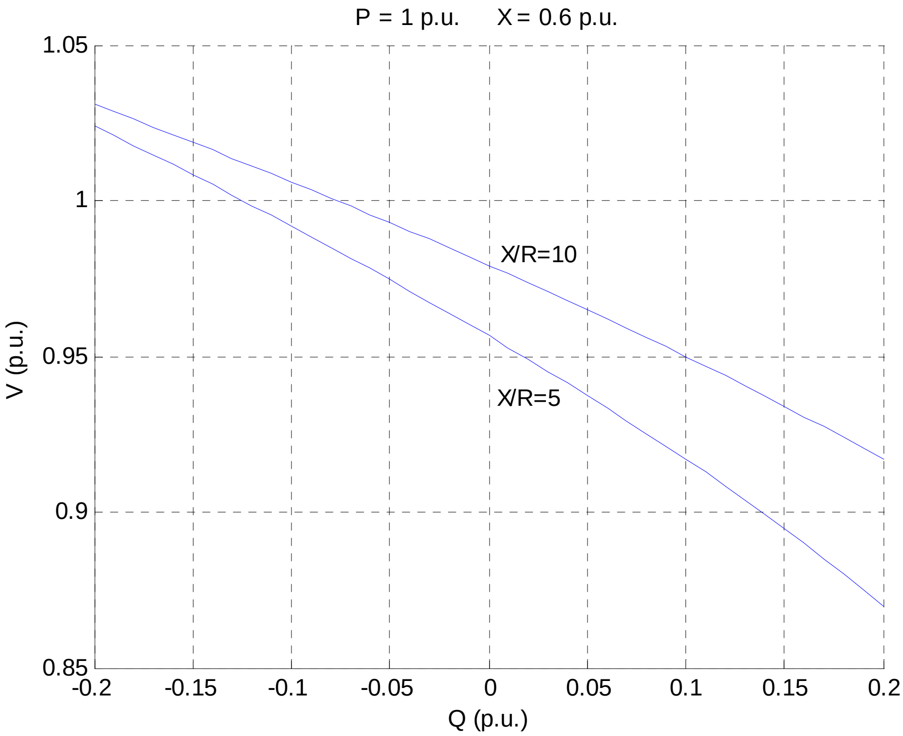


Figure 32: Voltage stability depending on the reactive power compensation.

The primary voltage regulation is done by synchronous generators and FACTS injecting reacting power to maintain the voltage constant. In the automatic voltage regulation the reactive power injected follows a certain Q/V curve that determines the reactive power reference depending on the voltage at the node that should be controlled.

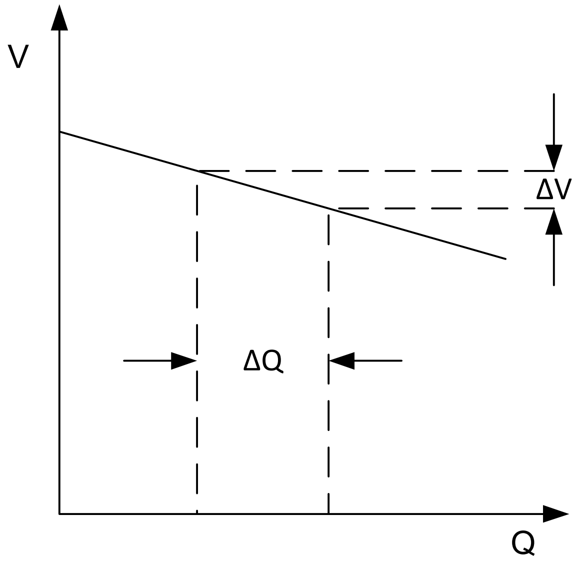


Figure 33: Voltage/reactive power drop characteristic.

4.2.1.1. Synchronous generator

The synchronous generator is able to modify its active and reactive power generation in a controlled and continuous way. The active power is controlled modifying the input flow of the turbine and the reactive power is controlled varying the excitation current and modify the internal electromotive force of the machine [47].

4.2.1.2. FACTS

A flexible alternating current transmission system (FACTS) is defined by the IEEE as "a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability"[48].

FACTS allow improving transient, dynamic and voltage stability [49-51]. They enhance the power flow controllability and they increase the power transfer capability of the AC transmission network.

There are three different connections to compensate a power line: shunt connection, series connection and shunt-series connection.

TABLE 4
FACTS CLASSIFICATION

	FACTS	
	Thyristors	Voltage source converter (VSC)
Shunt	Static Var Compensator (SVC)	Static Synchronous Compensator (STATCOM)
Series	Thyristor Controlled Series Compensator (TCSC)	Static Synchronous Series Compensator (SSSC)
Series&Shunt	TCPAR	UPFC

- Static Var Compensator (SVC): These devices employ fixed banks of capacitors, controlled with thyristors, which can switch them on and off rapidly. In many instances, there are also thyristor-switched inductors to prevent system resonance [52].
- Static Synchronous Compensator (STATCOM): STATCOM is one of the key FACTS Controllers. It can be based on a voltage sourced or current-sourced converter [53]. These devices are gate turn-off type thyristors (GTO) based SVCs. They are solid-state synchronous voltage generators that consist of multi-pulsed, voltage sourced inverters connected in shunt with transmission lines. They do not require capacitor banks and shunt reactors but rely on electronic processing of voltage and current waveforms to provide inductive or capacitive reactive power. They have the added advantage that their output is not seriously impacted by low system voltage [52].

  STATCOM is a subset of the broad based shunt connected controller which includes the possibility of an active power source or an ESS on the de side so that the injected current may include active power [54]. Due to this possibility the FACTS technology used in the present thesis is the STATCOM as modeled in the previous chapter.

- Thyristor Controlled Series Compensator: A thyristor controlled reactor is placed in parallel with a series capacitor, allowing a continuous and rapidly variable series compensation system [52].
- Static Synchronous Series Compensator: SSSC is a static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power [55].
- Thyristor-Controlled Phase Angle Regulator (TCPAR): It is a phase-shifting transformer adjusted by thyristor switches to provide a rapidly variable phase angle [53].
- Unified Power Flow Controller (UPFC): These devices have shunt connected STATCOM with an additional series branch in the transmission line supplied by the STATCOM’s dc circuit. These devices are comparable to phase shifting transformers. They can control all three basic power transfer parameters: voltage, impedance and phase angle [52].

4.2.2. Secondary voltage regulation

The secondary regulation controls the voltage in a small amount of nodes in each area; these nodes are called pilot nodes. For the secondary regulation a group of generators is assigned to each pilot node in order to maintain the voltage in these nodes. The secondary voltage regulation is an automatic and algorithmic control with a response time of several seconds. The control of the pilot nodes assures a stable voltage profile in the whole area.

In each control step of the secondary regulation a quadratic equation is solved to determine the actions on the control generators and OLTCs. Some of these pilot nodes might be controlled by OLTC while other pilot nodes might be controlled by reactive power compensators, even some pilot nodes might be controlled by different devices.

4.2.2.1. OLTC

The On-Load Tap Changer (OLTC) keeps the voltage at the secondary side of the transformer, which will be called the substation secondary bus voltage, constant by adjusting the tap position [56]. On-load tap changers may be generally classified as mechanical, electronically assisted, or fully electronic.

A mechanical tap changer physically makes the new connection before releasing the old using multiple tap selector switches, but avoids creating high circulating currents by using a diverter switch to temporarily place large diverter impedance in series with the short-circuited turns. This technique overcomes the problems with open or short circuit taps.

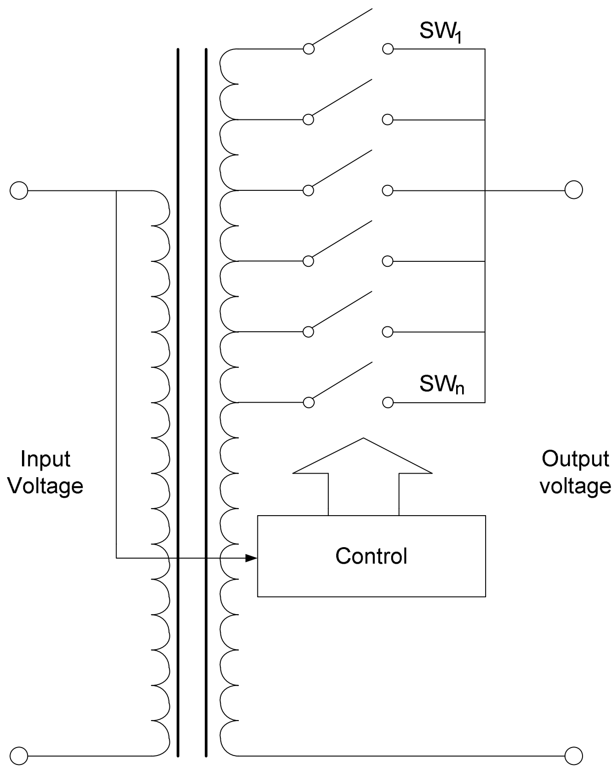


Figure 34: Scheme of an OLTC mregulator.

AC voltage stabilizers based on thyristor-commutated OLTC are reliable and have almost completely replaced mechanical switching equipment in low-voltage applications, single- and three-phase, ranging from 300 VA to 300 kVA. This replacement does not apply to the mechanical tap-changers associated to feeding transformers of long medium-voltage lines (typically 69 kV primary, 34.5 kV secondary, 10 MVA), usually housed in the transformer tank, needing periodical renewal of switches and isolating oil [57]. The continuous growth of power semiconductor devices, such as the insulated gate bipolar transistor, allows the development of fast OLTC regulators [58].

4.3. Frequency regulation

For a satisfactory operation of a power system, the frequency should remain nearly constant. The control of frequency ensures constancy of speed of induction and synchronous motors, assuring their satisfactory performance, as they are highly dependent on the performance of all the auxiliary drives associated with the fuel, the feed-water and the combustion air supply system. In a network, considerable drop in frequency could result in high magnetizing currents in induction motors and transformers. The use of electric clocks and the use of frequency for other timing purposes require accurate maintenance of synchronous time which is proportional to the integral of frequency [13]. A large frequency deviation can damage equipment, degrade load performance, cause the transmission lines to be overloaded and can interfere with system protection schemes, ultimately leading to an unstable condition for the power system [59]. Violation of frequency control requirements is known as a main reason for numerous power grid blackouts. It could also result in overloading transmission lines as various generators try to restore system frequency impacting markets efficiency. Generator protective systems take action to prevent generator damage but exacerbate the overall generation/load imbalance [60].

Sudden unpredicted variations in renewable energy sources (i.e. variations on wind speed) may lead to disturbances especially in weak networks (small power systems) with high penetration of renewable energy. The increasing penetration of DG and wind farms will have larger impact on frequency regulation requirements. This is because increasing wind generation will necessarily reduce the contribution from other generation sources if the load remains constant. The displaced generation is likely to be the marginal generation that is least economical to run (as opposed to the lowest-cost base load generation). This displaced marginal generation is also the generation that has maneuvering capability and often supplies regulation to the power system.

Small isolated power systems are particularly vulnerable to the occurrence of large frequency deviations affecting the security of the system. The main characteristic is the low value of the inertia constant due to the reduced number of generators connected to the system and the fact that most of the generators in isolated systems are driven by diesel engines. When a generator trips, these power systems may exhibit high initial rates of frequency decay. When a generator trips, not only a large amount of generation can be lost, but inertia also, both factors contributing to a high value of the initial slope of the frequency. This fact makes the existing spinning reserve useless in some cases, since it cannot be fast enough to arrest the frequency decay. To address these issues, usual actions and limitations are: load shedding (by under-frequency relays and rate of frequency relays), minimum spinning reserve, load reconnection limitation, and wind power generation limitation (sometimes restricted during operation in isolated power systems for fear of a sudden trip of wind generation which can lead to load shedding).

The high price of frequency regulation coupled with the good match between the technical capabilities of some storage technologies and the requirements of the power system make frequency regulation an attractive market for storage projects [61].

The frequency of a power system depends on its active power balance. The change of active power demand should be responded by the different generators supplying power to the system, as equation (4. 8) defines. Figure 35 represents the main factors to analyze the frequency variation in a power system. All the power consumed by the loads connected to the grid and the losses through the electrical grid have to be supplied by the different generators connected to the system. To analyze the frequency response of a power system it is convenient to classify the loads between resistive loads and frequency dependent loads (induction machines for example).

$$\sum_{i=1}^{i=N} P_{Ei} = \sum_{j=1}^{j=R} P_{Lj} + \sum_{k=1}^{k=S} P_{Mk} + line\,losses \qquad (4.\ 8)$$

The response of the power system and the synchronous generators to a change in power balance, together with the resulting frequency deviations can be divided into three phases [19]. In the first phase, when controllers have not yet been activated, the rotor of the synchronous generators releases or absorbs kinetic energy; as a result, the frequency changes. The response is mainly determined by the equation-of-movement of the system and is called inertial response here, as the inertia dampens the frequency deviations.

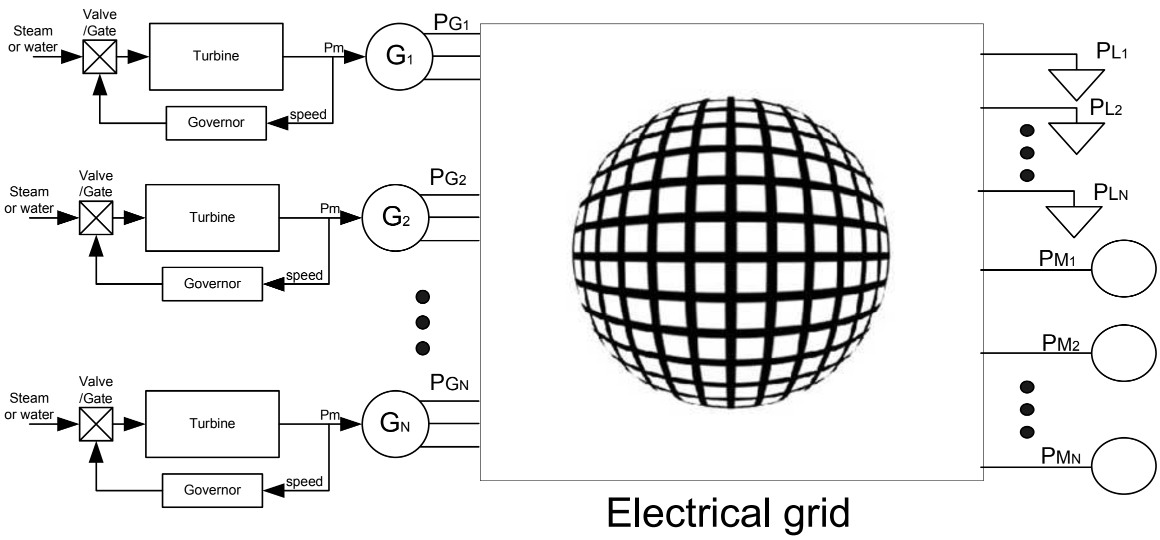


Figure 35: Frequency regulation in the electrical grid

When the frequency deviation exceeds a certain limit, controllers are activated to change the power input to the prime movers. This is the second phase, the primary frequency control.

After restoration of the power balance there is still a steady-state frequency deviation. In the third phase, secondary frequency control, the frequency is brought back to its nominal value.

4.3.1. Frequency behavior

When there is a load change, it is reflected instantaneously as a change in the electrical torque output T_E of the generator. This causes a mismatch between the mechanical torque T_{mec} and the electrical torque, resulting in a speed variation as determined by the equation of motion (note that all the parameters in this section will be given in pu):

$$\Delta\omega_r = \frac{1}{2Hs}\left(T_{mec} - T_E\right) \tag{4. 9}$$

The rate of change is determined by the inertia constant H, which is defined as:

$$H = \frac{J\omega_o}{2S} \quad (4.10)$$

Where J is the inertia moment (Kg·m^2), ω_o is the nominal angular velocity and S is the nominal power.

For load frequency studies, it is better to express this relationship in terms of power. Expressing the speed in p.u. the relationship can be expressed with the following expression, as explained in [13]:

$$\Delta\omega_r = \frac{1}{2Hs}\left(\Delta P_{mec} - \Delta P_E\right) = \frac{1}{Ms}\left(\Delta P_{mec} - \Delta P_E\right) \quad (4.11)$$
$$M = 2H$$

Load response to frequency deviation

In general power system loads are a composite of a variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical load is independent of frequency. In the case of motor loads, the electrical power changes with frequency due to changes in motor speed.

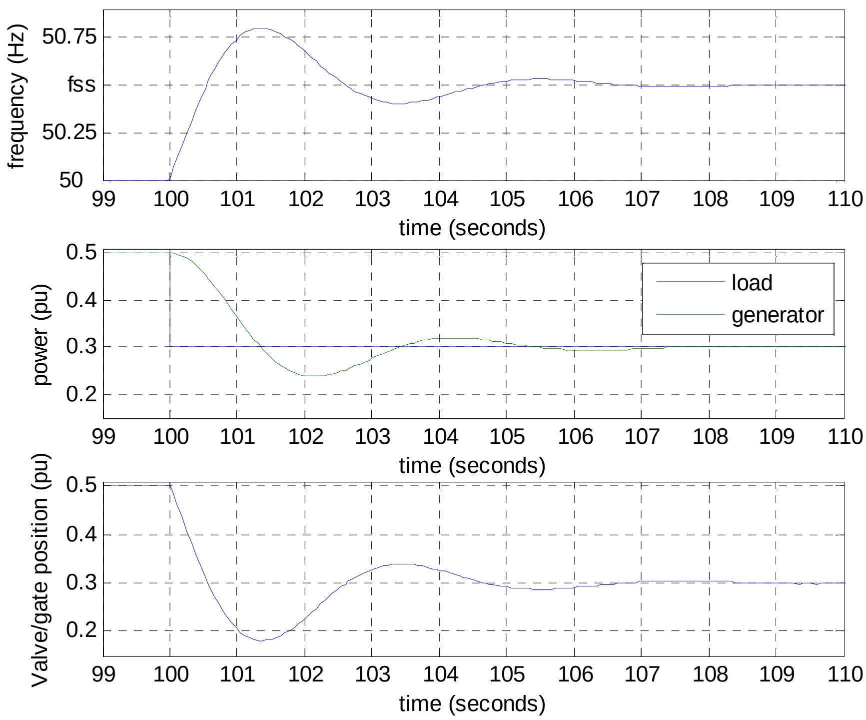


Figure 36: Response of a reheat steam turbine in the face of a load disconnection

It is necessary to model this frequency load response in order model the behavior of the system in the face of frequency variations. Frequency dependence is usually represented by equation (4. 12) where f is the actual frequency, f_0 is the rated frequency, while k_{Pf} and k_{Qf} are the model frequency sensitivity parameter. Using the exponential model this gives [62]:

$$P = P(V)\left[1 + k_{Pf}(f - f_0)\right]$$
$$Q = Q(V)\left[1 + k_{Qf}(f - f_0)\right] \quad (4.\ 12)$$

Where P(V) and Q(V) represent any type of the voltage characteristic and k_{Pf}, k_{Qf} are the frequency sensitivity parameters.

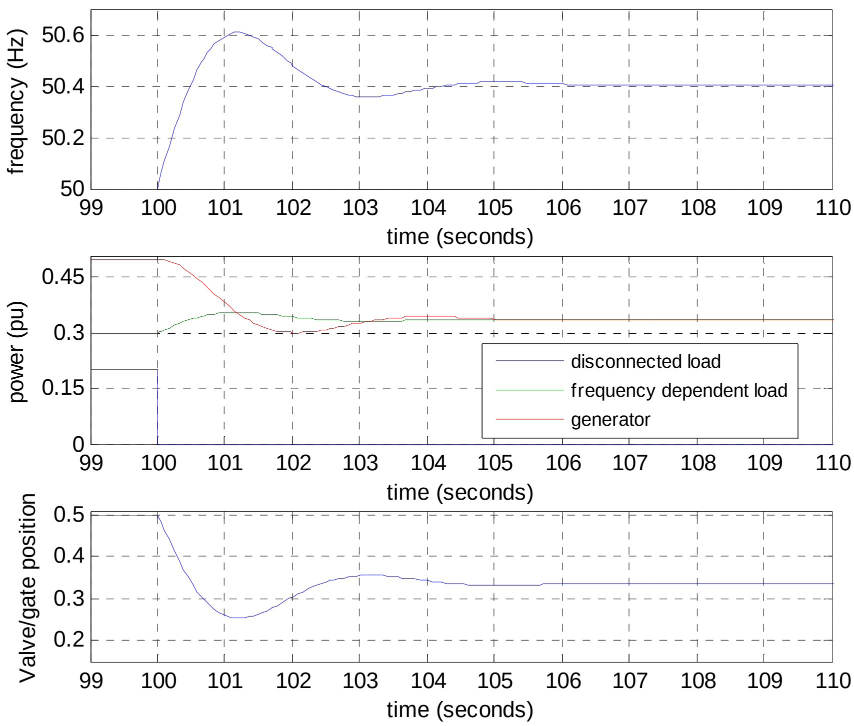


Figure 37: Response of a reheat steam turbine in the face of a load disconnection with a frequency dependent load

The frequency dependant characteristic can be also expressed by the load-damping constant (D) which defines the percent change in load for one percent change in frequency. The variation of speed including this effect is given by the following equation [13]:

$$\Delta\omega_r = \frac{1}{Ms + D}\left(\Delta P_{mec} - \Delta P_L\right) \tag{4. 13}$$

Composite regulating characteristic of power systems

In the analysis of load-frequency controls the interesting issue is the collective performance of all generators in the system, in this case it is assumed the coherent response of all generators and there are represented by an equivalent generator. The inertia of this equivalent generator (Meq) is the sum of the inertia constants of all the generators of the system. The mechanical power variation of this equivalent generator is given by the sum of the mechanical power of all the generators subtracting the power consumption in the system. The speed of the equivalent generator represents the system frequency and in per unit the two are equal.

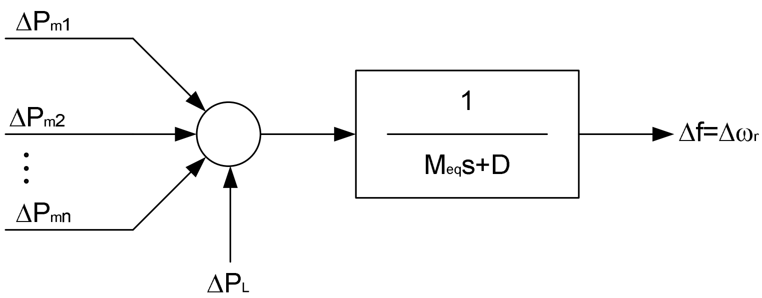


Figure 38: System equivalent for load-frequency control equivalent

4.3.2. Primary frequency regulation

The governors are provided with a characteristic so that the speed drops as the load is increased. The typical speed-droop control configuration is shown in Figure 39.

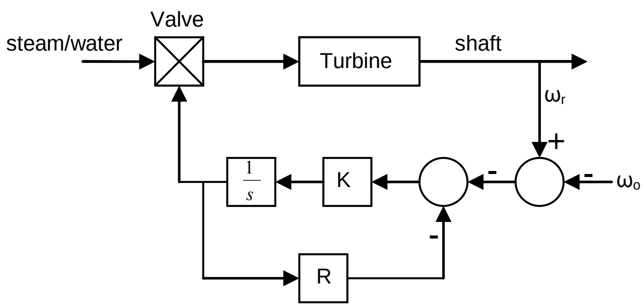


Figure 39: Governor with speed-droop characteristic

The value of R determines the steady state speed versus load characteristic of the generating unit. The ratio of speed deviation or frequency deviation to change in valve/gate position or power output is equal to R.

$$R = \frac{percent\ speed\ or\ frequency\ change}{percent\ power\ output\ change} = \frac{\omega_{NL} - \omega_{FL}}{\omega_o} \quad (4.14)$$

Where ω_{NL} is the steady state speed at no load, ω_{FL} is the steady-state speed at full load and ω_o is the nominal speed.

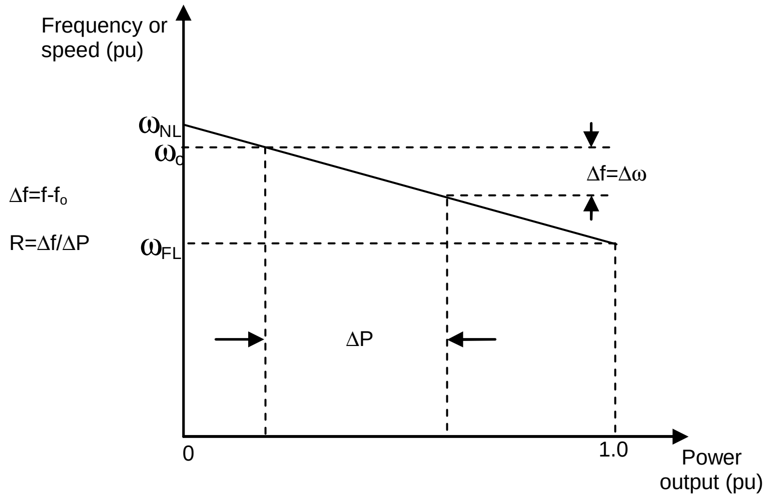


Figure 40: Ideal steady-state characteristics of a governor with speed droop

If two or more generators are connected to a power system, there will be a unique frequency at which they will share a load change. When a load increase causes the units to slow down, the governors increase output until they reach a new common operating frequency, depending on their droop characteristic.

The composite power/frequency characteristic of a power system thus depends on the combined effect of the droops of all generator speed governors. It also depends on the frequency characteristics of all the loads in the system. For a system with n generators and a composite load-damping constant of D, the steady-state frequency deviation following a load change is given by equation (4. 15).

$$\Delta f_{SS} = \frac{-\Delta P_L}{(1/R_1 + 1/R_2 + ... + 1/R_n) + D} \qquad (4.15)$$

4.3.3. Secondary frequency regulation

With primary speed control action, a change in system load will result in a steady-state frequency deviation. Restoration of system frequency to nominal value requires supplementary (secondary) control action which adjusts the load reference setpoint. The integral control action ensures zero frequency error in the steady state. The secondary control action is slower than the primary speed control.

The relationship between speed and load can be adjusted by changing an input shown as load reference setpoint in Figure 41:

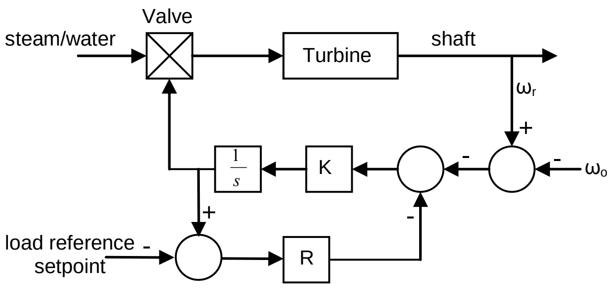


Figure 41: Schematic diagram of governor and turbine

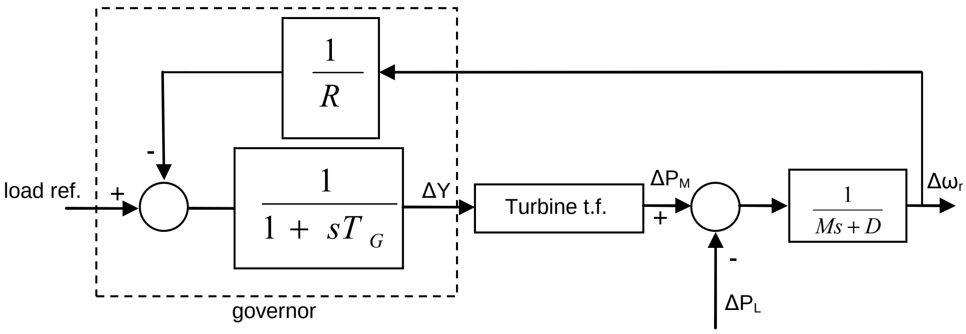


Figure 42: Reduced block diagram of Governor and turbine

The adjustment of load reference setpoint is accomplished by operating the speed changer motor. Thus the power output of the generating unit at a given speed may be adjusted to any desired value by adjusting the load reference setting through actuation of the speed changer motor. When two or more generators are operating in parallel, the speed-droop characteristic of each generating unit merely establishes the proportion of the load picked up by the unit when a sudden change in system load occurs. The output of each unit at any given system frequency can be varied only by changing its load reference, which in effect moves the speed-droop characteristic up and down.

The secondary regulation is done adding an integral control to the units selected for the Automatic Generation Control. The load reference is adjusted in order to restore the frequency to the nominal value.

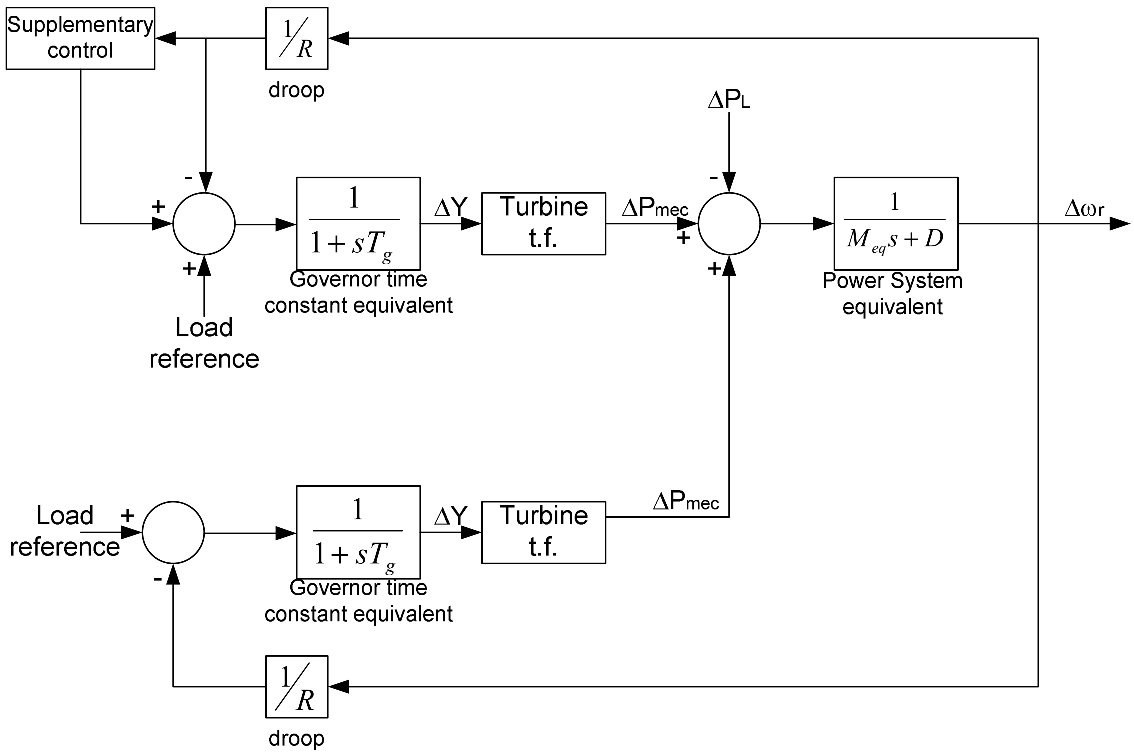


Figure 43: Addition of integral control on generating units selected for AGC

4.3.4. Underfrequency load-shedding

Severe system disturbances can result in cascading outages isolation of areas, causing formation of electrical islands. If such an islanded area is undergenerated it will experience a frequency decline. This decline may reach levels that could lead to tripping several generation units by underfrequency protective relays, aggravating the situation. To prevent extended operation of separated areas at lower than normal frequency, load-shedding schemes are employed to reduce the connected load to a level that can be safely supplied by available generation [13].

4.4. Conclusions

Voltage and frequency stability are the most important problems related to the massive integration of DG in small electrical grids. These two problems have been analyzed in this chapter and their regulation has been discussed. Compensation of active and reactive power is necessary to control these variables.

In the following chapters the contribution of Energy Storage Systems to solve these two problems will be analyzed with the simulation tool presented in the previous chapter.

Chapter 5

Energy Storage Systems for Grid Support applications

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5. Energy Storage Systems for Grid Support applications

5.1. Introduction

In the previous chapter voltage and frequency regulation were analyzed. Using the models and simulation tools developed in chapter 3 voltage and frequency stability problems might be analyzed.

The aim of this chapter is to analyze the contribution of Energy Storage Systems (ESS) to improve the integration of Distributed Generation (DG) in different scenarios. The contribution of ESS will be analyzed for three different applications: voltage regulation, frequency restoration in the face of a large frequency deviation and primary frequency regulation.

5.2. ESS for voltage regulation

Voltage stability is one the main obstacles for the massive integration of Distributed Generation (DG), because the actual network operation is designed for a unidirectional power flow [5, 14]. In this sense many authors have analyzed the problematic issues of voltage control in distribution networks with high penetration of DG. In [15-17] the authors analyzed the use of OLTC power transformers to control the voltage levels in the MV distribution grids, in presence of a high level of DG. Due to the increasing penetration of DG in the LV distribution network the control of these grids becomes more complicated. In fact, it is necessary the control of the voltage levels in these networks.

Other authors [18] discussed about the use of inverters for voltage control applying reactive power compensation. The coordinated use of reactive power compensation using switching capacitors and OLTCs it is discussed in [63]. The use of different voltage control technologies in distribution grids with high penetration of wind power DG is analyzed in [64]. It is not common to use OLTCs in substations from MV to LV but there are some proposals in the literature [15, 63].

The use of energy storage systems connected through power converters to the distribution grid it is also interesting to maximize the integration of DG, as it has been demonstrated by several authors [65, 66].

5.2.1. Scenario for the study

The scenario proposed for this study is composed by a Wind Farm connected to a MV/LV transformer substation through low voltage 690v three-phase grid. This substation is considered a pilot node for the secondary voltage regulation, so primary and secondary control actions are considered at this substation.

The equivalent grid of the distribution network is modeled as an ideal voltage source with a short-circuit impedance, Z_{sc} in Figure 49. In order to simulate a weak network, this short circuit impedance for a short circuit power of 550kW. This scenario will be analyzed for different X/R ratios for this Z_{sc} impedance. It is known that at Low Voltage levels the X/R ratio could be as low as 2, so the range of values analyzed are from 1 to 10. The impedance of the substation is taken into account in this Z_{sc} impedance.

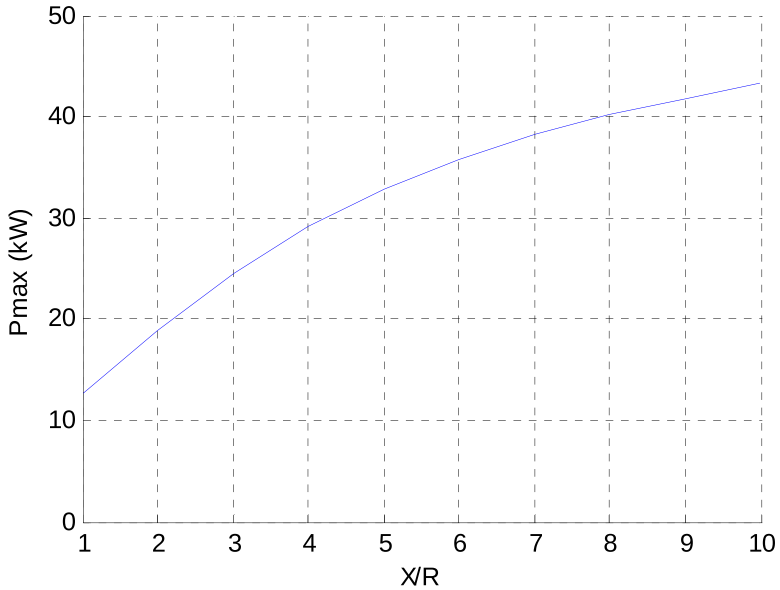

Figure 44: The maximum power that can be injected in the analyzed scenario depending on the X/R ratio of the network

5.2.2. Analytical study

The change from centralized electrical grids to distributed ones, in which many generation units are connected to distribution networks, has increased the problems related to voltage stability because the power flows of DG go upstream rising the voltage in the connection points (PCC).

The voltage rising is a serious problem in some nodes especially in rural networks with low load demand. The maximum voltage limit defines the maximum power that can be injected to a node.

To analyze the voltage rise in the PCC, the distribution network equivalent is modeled as an ideal voltage source with a short-circuit impedance, Z_{sc} in Figure 45.

$$Z_{sc} = R + jX \tag{5. 1}$$

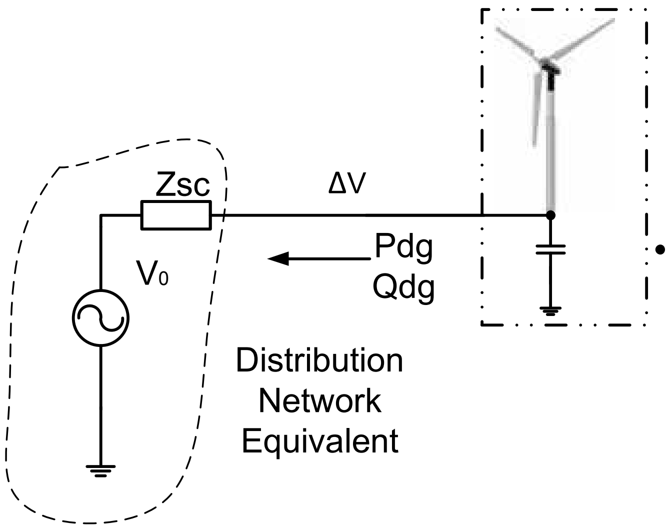

Figure 45: Connection point of a Distributed Generator

From equations (4. 5) and (4. 7), of the previous chapter, the voltage amplitude in the distribution line equivalent impedance is given by:

$$|V| = \sqrt{\frac{1}{4}\left[1 \pm \sqrt{1 - 4\left(\left(\frac{XP_{DG} - RQ_{DG}}{V_0}\right)^2 - \left(RP_{DG} + XQ_{DG}\right)\right)}\right]^2 + \left(\frac{XP_{DG} - RQ_{DG}}{V_0}\right)^2} \qquad (5.\ 2)$$

Where P_{DG} and Q_{DG} are the active and reactive power injected in the PCC, R and X are the equivalent resistive and inductive impedance upstream of this PCC (Z_{sc}), V_0 is the distribution grid equivalent voltage and ΔV is the voltage variation in this equivalent impedance.

Figure 46 shows, for the power system of Figure 45, curves of the V-P relationship for different values of load power factor. The locus of critical operating points is shown by the dotted line in the figure. Normally, only the operating points above the critical points represent satisfactory operating conditions. Thus a sudden variation of the power factor may cause an unstable operating condition, represented by the points below the critical points.

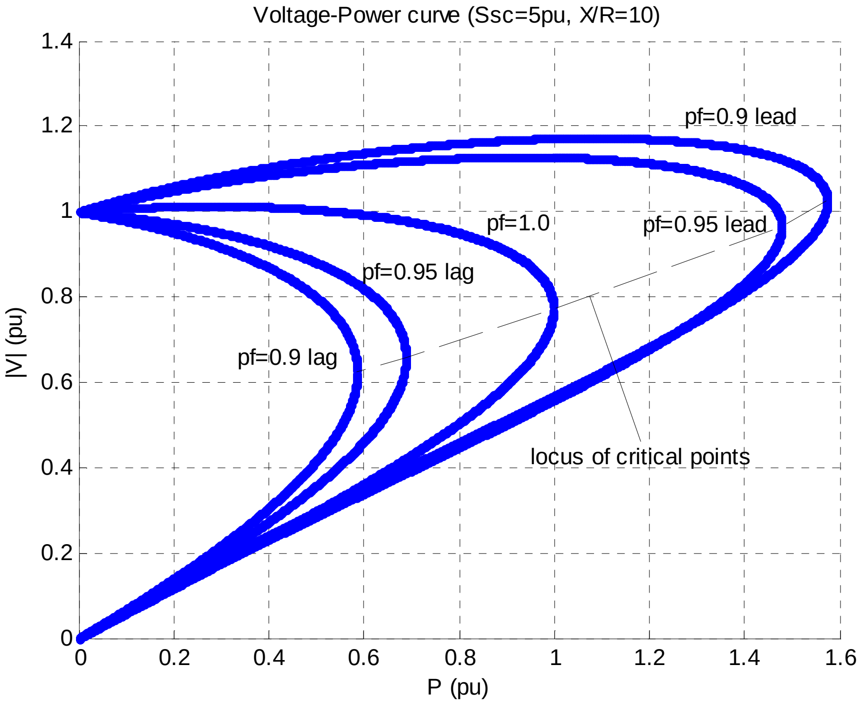

Figure 46: Voltage Power curve for an X/R ratio of 10

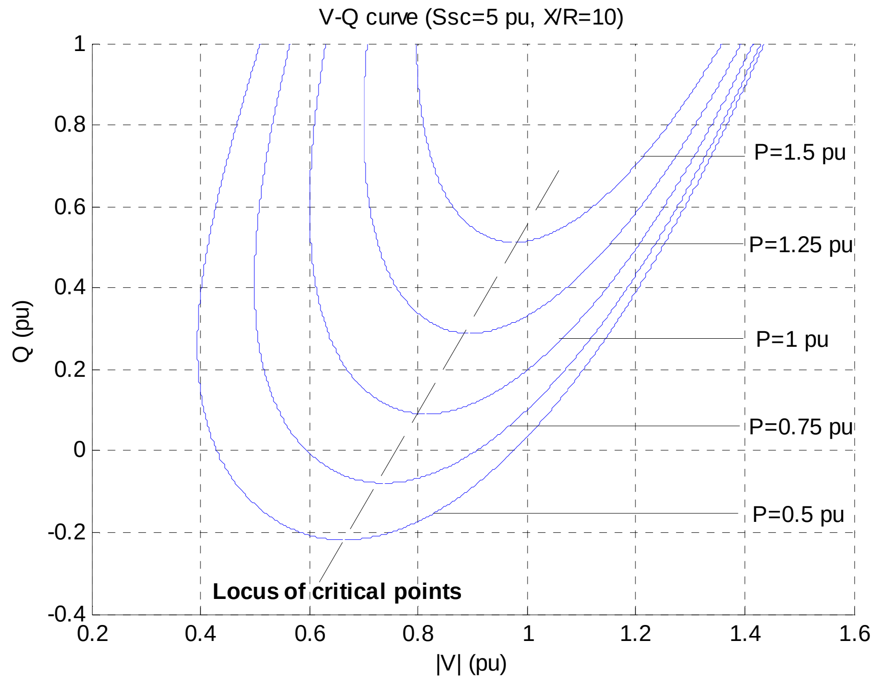

Figure 47: Reactive power Voltage curve for an X/R ratio of 10

The influence of the reactive power is more apparent in Figure 47. It shows a family of curves applicable to the feeder of Figure 45, each of which represents the relationship between V and Q at the PCC for a fixed value of P. The system is stable in the region where the derivative is positive.

These two figures show that the reactive power compensation permit to inject more power in one node. The maximum power injection increases with the reactive power supply.

Figure 48 shows the maximum power that the maximum power that the maximum power that can be injected in the substation depending on the reactive power compensation at the PCC, for different X/R ratios. For low X/R ratios the ability to control the voltage by the reactive power compensation is reduced drastically.

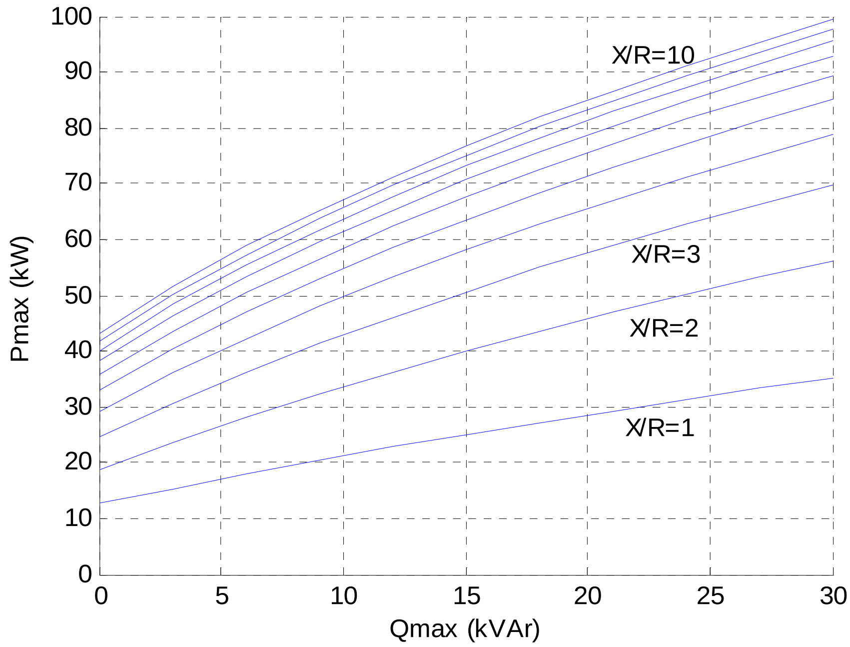

Figure 48: Maximum power injection in the substation depending on the reactive power compensation

5.2.3. Active Substation solution

At this point an Active Substation is proposed for a substation located in a weak area of an electrical grid. The installation of active support technologies in this kind of substations will contribute to solve voltage stability problems in remote areas where the electricity consumption is low and the installed DG power is large. The contribution of this Active Substation to the voltage stability is analyzed.

Active Substation is a concept in which the voltage level at the substation is controlled using local measurements and the management of different control devices connected to the MV/LV substation. All the measurements are local measures, the control devices are installed within the substation and there is no need to control/coordinate the DG units connected downstream the substation. Using Active Substations it is possible to increase the DG power injected to a weak network.

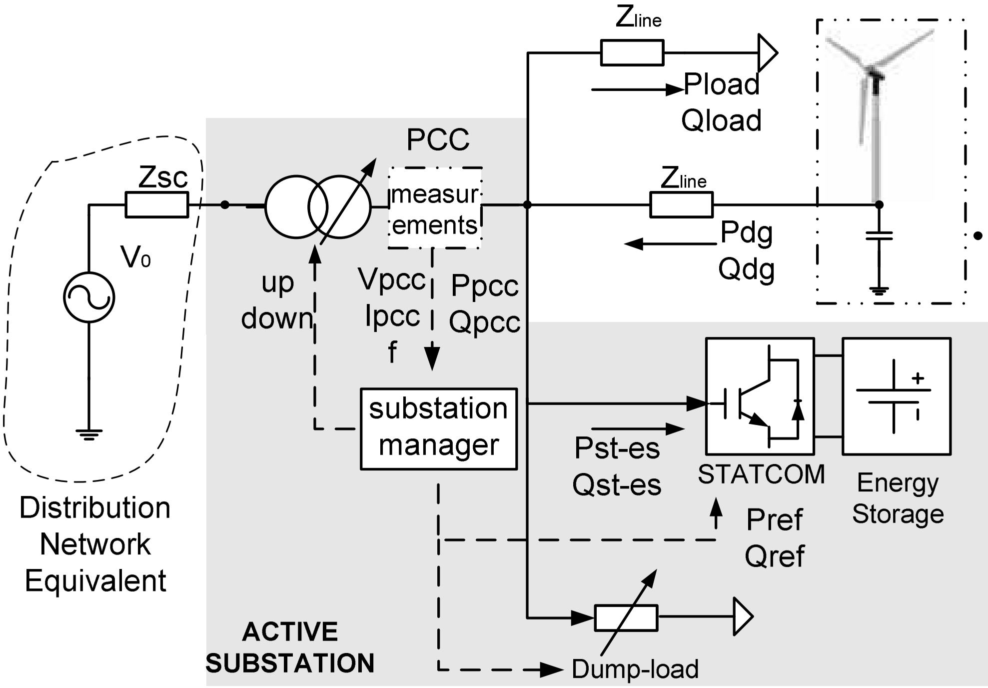

Figure 49: A distribution network example with DG, where an active substation controls an OLTC, a dump-load and a STATCOM with energy storage

To maintain the voltage within acceptable limits at the point of common coupling (PCC), the power injected to the distribution grid should be limited. It is defined as PCC the point where the different lines are connected to the substation.

In this context it is necessary to install control devices to improve the integration of DG. The Active Substation where the DG is connected is the best placement in order to control the upstream power flow, monitoring the electrical signal in the substation and acting on the signal using the installed control devices.

The installation of an Energy Storage System in a substation is proposed in order to become an Active Substation. The maximization of DG power is analyzed using an ESS and local measurements. This ESS may control the active and reactive power flow at the substation and it might be coordinated with other devices like OLTCs to control the voltage. A dumpload to consume the surplus energy is also considered in this Active Substation.

Management algorithm

A management algorithm is proposed to control the Active Substation. This algorithm will regard to maintain always the voltage within a limit of ±5% of the nominal voltage, maximizing the power that may be injected to the substation. In normal work conditions the system always tries to maintain the voltage in its nominal value.

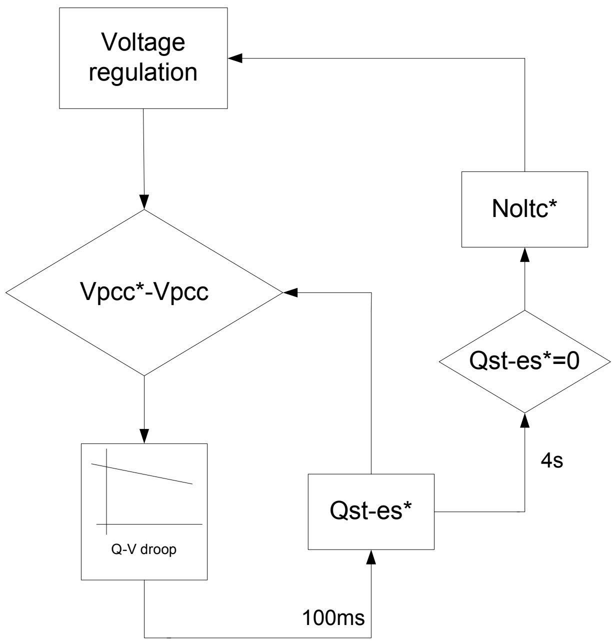

Figure 50: Flux diagram of the proposed algorithm.

Due to its fast response the primary control loop will control the reactive power compensation ($Q_{st\text{-}es}$) of the STATCOM+Energy Storage, the reference reactive power (Q*) will be defined by a PI controller excited by the error between the measured voltage (V) and the nominal voltage (V_n). The secondary slower loop will control the OLTC, since the OLTC is much slower than the STATCOM+Energy Storage. The OLTC will act to reduce the power compensation of the ST-ES, in this way if Qst_{-es} is larger than a certain value (10% of maximum, for example) the OLTC will make a step down or up depending on the sign of the reactive power.

Using a Battery to absorb the surplus power of the Wind Farm the installed power may be maximized. If the power demand is excessive as well, the battery will provide the necessary power. When the battery is fully charged a dump-load can be used to absorb the excessive power production, while the only solution for excessive consumption will be the limitation of the power.

5.2.4. Simulation results

The management algorithm proposed above will be implemented in a simulation, for the following Active Substation. The weak network proposed will be simulated with an X/R ratio of 6. The OLTC will be sized with a maximum voltage control capacity of ±10% and steps of 2%, with a response time of 4 seconds. A 15kW battery in a 22.5kVA ST-ES, this gives the chance for a simultaneous injection of 15kW and 15kVAr. The maximum power that can be injected to this Active Substation without using the battery it is shown in Figure 51 in function of the voltage in the network equivalent.

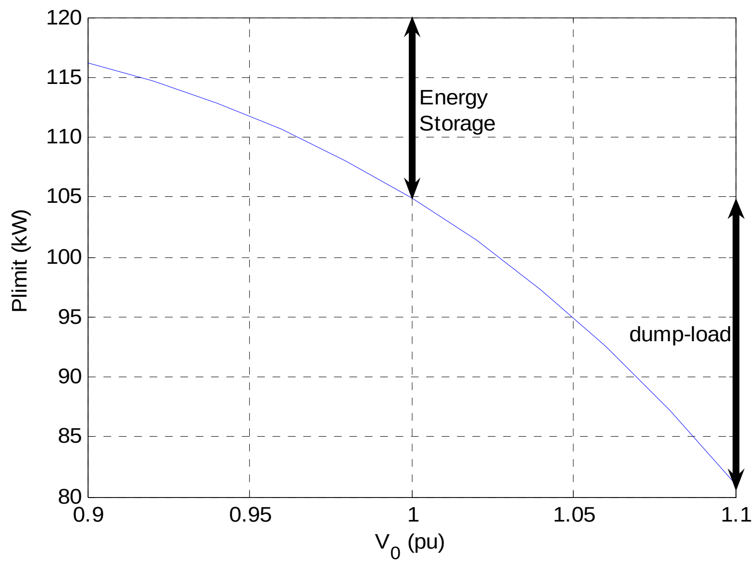

Figure 51: The maximum power that can be injected in the simulated scenario, depending on the

Figure 51 shows that the maximum power that can be connected to this substation has increased up to 120kW (105kW+15kW of the battery), in normal conditions. For cases where the voltage in the upstream network increases it would be necessary to use a

Dump-load. Regarding the previous graph a 25kW Dump-load would be necessary to answer against an increase of 10% in the upstream voltage.

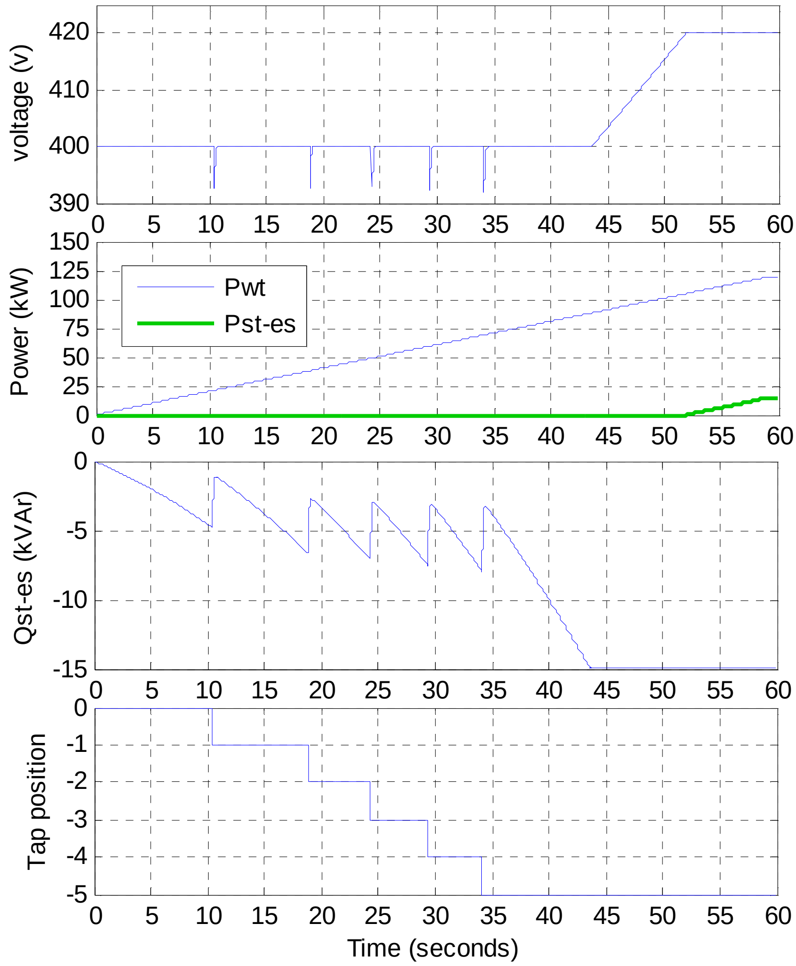

Figure 52: Temporal simulation of the system for a fast increase in the injected power.

The following simulation results show how the system works, for a wind farm of 120kW connected to the Active Substation. In the first case it is shown how the system would answer for an increase in the power injected from 0 to 120kW without any load connected to the substation. It is not a real case but it shows how the system would be able to answer to such an adverse situation.

In Figure 52 the power injected to the substation is increasing since the beginning. The voltage is controlled by the ST-ES injecting reactive power. When the reactive power is higher than a certain level the OLTC orders to change a tap and after 4 seconds it changes. When there is a tap change the reactive power compensation is reduced very fast due to the fast response of the STATCOM+Energy Storage, although it keeps on increasing because the active power injected to the substation is also increasing. After the 5 possible tap changes and the reactive power compensation in its maximum (15kVAr) the voltage cannot be maintained in its nominal value. When the voltage at the PCC reaches an overvoltage of 5% the STATCOM+Energy Storage starts injecting active power to maintain the voltage below this value.

In the second simulation it is shown the response of the substation in a case of a load that is suddenly disconnected, while the wind farm is working with mid power.

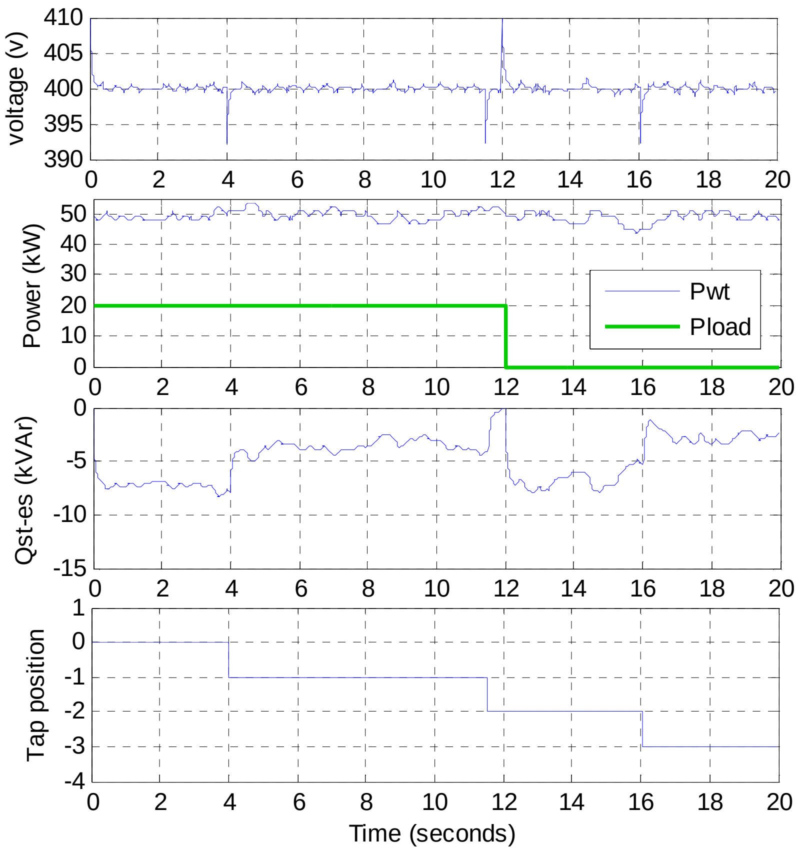

Figure 53: Temporal simulation of the system for a suddenly disconnected load.

In Figure 53 it is shown how using the reactive power compensation the voltage is controlled in the beginning. After 4 seconds the OLTC changes a tap to reduce the injected reactive power. A second tap change happens afterwards reducing the injected reactive power. When in the 12th second of the simulation the 20kW load is disconnected the voltage is controlled increasing the reactive power compensation. After 4 seconds the OLTC changes a tap reducing again the reactive power.

In these simulations we can see that the tap changes of the OLTC can be reduced by injecting more reactive power, these two variables should be taken into account to design the substation, because normally it will be more interesting to reduce tap changes than to reduce the reactive power compensation.

The coordinated control of different devices connected to a substation will maximize the Distributed Generation that may be injected to this substation. In the face of a large increase of DG power in rural areas Active Substations are demonstrated as a solution to make the most of the installed renewable energies.

5.3. ESS for frequency restoration in insular grids

Small isolated power systems are particularly vulnerable to the occurrence of large frequency deviations affecting the security of the system [67, 68]. The main characteristic is the low value of the inertia constant due to the reduced number of generators connected to the system and the fact that most of the generators in isolated systems are driven by diesel engines. When a generator trips, these power systems may exhibit high initial rates of frequency decay. Not only is a large amount of generation lost, but inertia also, both factors contributing to a high value of the initial slope of the frequency. This fact makes the existing spinning reserve useless in some cases, since it cannot be fast enough to arrest the frequency decay. To address these issues, usual actions and limitations are: load shedding (by under-frequency relays and rate of frequency relays), minimum spinning reserve, load reconnection limitation, and wind power generation limitation (sometimes restricted during operation in isolated power systems for fear of a sudden trip of wind generation which can lead to load shedding).

An alternative to avoid these usual actions and limitations is the use of fast response ESS [69], in order to supply power very fast and avoid large frequency deviations after a generator trip in a weak electrical grid. In weak electrical grids the disconnection of one generator can lead to a large frequency deviation in a first instant since the inertia of one generator may be an important part of the overall system inertia. After a few seconds the frequency can be restored by the primary response of the rest of the generators but in the first instance the frequency deviation might fall under the security limits.

SMES, Flywheels and Ultracaps are the available solutions for fast response ESS [70]. SMES is a very expensive solution. Flywheels and Ultracaps [71] therefore, are probably the best solutions for the proposed application. Considering an island as one of the most common scenarios for weak electrical grid where this phenomenon can occur, the problem of space should be taken into account. Since Ultracaps have better energy density compared to Flywheels, the former seems to be the best solution to install in regions with limitations of space.

5.3.1. Analytical study of the problem

The maximum frequency dip in a power system will be defined by the derivate of frequency variation. The frequency variation derivate in a power system is dependent on the equivalent inertia of the system. If one generator is disconnected the overall frequency behavior will change:

$$\frac{d\Delta f'(pu)}{dt} = \frac{\Delta P_{tot}(pu)}{M_{eq}'} \xrightarrow{disc} \frac{d\Delta f''(pu)}{dt} = \frac{\Delta P_{tot}(pu)}{M_{eq}''} \qquad (5.\ 3)$$

The power variation ΔP_{tot} is the difference between the electric power variation and the variation of the mechanical rotational power. The pu variation of the overall rotational speed of the system is:

$$\Delta\omega_r(s) = \frac{1}{M_{eq}''s}\left(\Delta P_{mec}(s) - \Delta P_E(s)\right) \qquad (5.\ 4)$$

The variation of the mechanical rotational power is given by the sum of responses of different generators connected to the electrical system:

$$\Delta P_{mec}(s) = \sum_{i=1}^{i=N} G_i(s)\left(\Pr ef_i - \frac{\Delta\omega_r}{R_i}\right) \qquad (5.\ 5)$$

Where $G_i(s)$ is the transfer function of each generator, R_i is the droop characteristic of each governor and $Pref_i$ is the reference mechanical power settled for each generator.

From equations (5. 4) and (5. 5) the overall rotational speed is defined by:

$$\Delta\omega_r(s) = \frac{\sum_{i=1}^{i=N}(G_i(s)\mathrm{Pr}ef_i) - \Delta P_E}{M_{eq}''s + \sum_{i=1}^{i=N}\left(\frac{G_i(s)}{R_i}\right)} \quad (5.\ 6)$$

The reference mechanical power is constant during the first seconds after the disconnection of a generator. Thus the response of the system during the first seconds after the disconnection is defined as:

$$\frac{\Delta\omega_r(s)}{\Delta P_E} = -\frac{1}{M_{eq}''s + \sum_{i=1}^{i=N}\left(\frac{G_i(s)}{R_i}\right)} \quad (5.\ 7)$$

The electrical power variation during the event of disconnection is the sum of the disconnected power and the difference in line losses, but this value might be neglected.

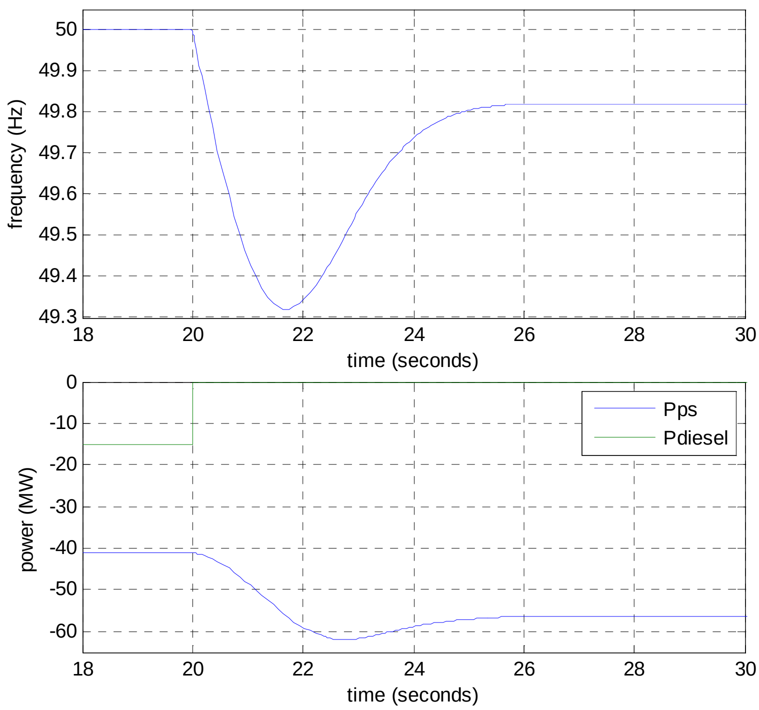

Figure 54: Frequency response in the face of the disconnection of a generator.

Figure 54 shows the response of the system in the proposed scenario for a sudden disconnection of the diesel generator.

The maximum frequency deviation accepted in the operation of the Spanish electrical grid is 0.5Hz. Below this value starts the emergency operation (P.O.-1.6), in which several devices are disconnected from the grid.

The use of an Ultracaps ESS may be enough to maintain the frequency within acceptable values during the transient frequency variations, due to generator disconnection. It is required a fast power supply during 1 or 2 seconds.

5.3.2. Scenario for the case study

To analyze these problems it is proposed a weak insular grid with high penetration of renewable energies. The insular grids have some differences in opposition to interconnected grids [72, 73]:

- Weak short circuit power.
- A high sensitivity in the face of variations on the generation.
- Capacity limitation of new generation resources.

Due to the last two features presented above the sizing of Primary Power Reserve is considerable percentage of the total power generated in the network at any given time. This is contrary to what happens in interconnected systems in which the primary reserve values are very small compared to the total power generated in the network. These characteristics of island networks make very interesting the use of ESS in order to reduce the size of reserve power and also to install more renewable energy sources which are not controllable.

A scenario composed by 6 nodes will be considered at this point. The scenario will be composed by a main reheat power station, a diesel power plant and one wind farm, as it is shown in Figure 55. The power consumption is distributed through all the nodes, as it is shown in Table 5. The line impedances in pu are shown in Table 6. The system will be analyzed as a unifilar representation in pu units. The nodes are HV posts, the base voltage is V_{base}=63kV and base power S_{base}=55.65MVA.

The main power station should be sized to supply all the power required by the island and a certain amount of reserve power for frequency regulation, the power station will be composed by 2 reheat steam generators of 30MW. An additional diesel generator is placed at node 3 with a nominal power of 15MW. A non-controlled wind farm is at node 6, with an installed power of 20MW. The ESS is installed at node 6.

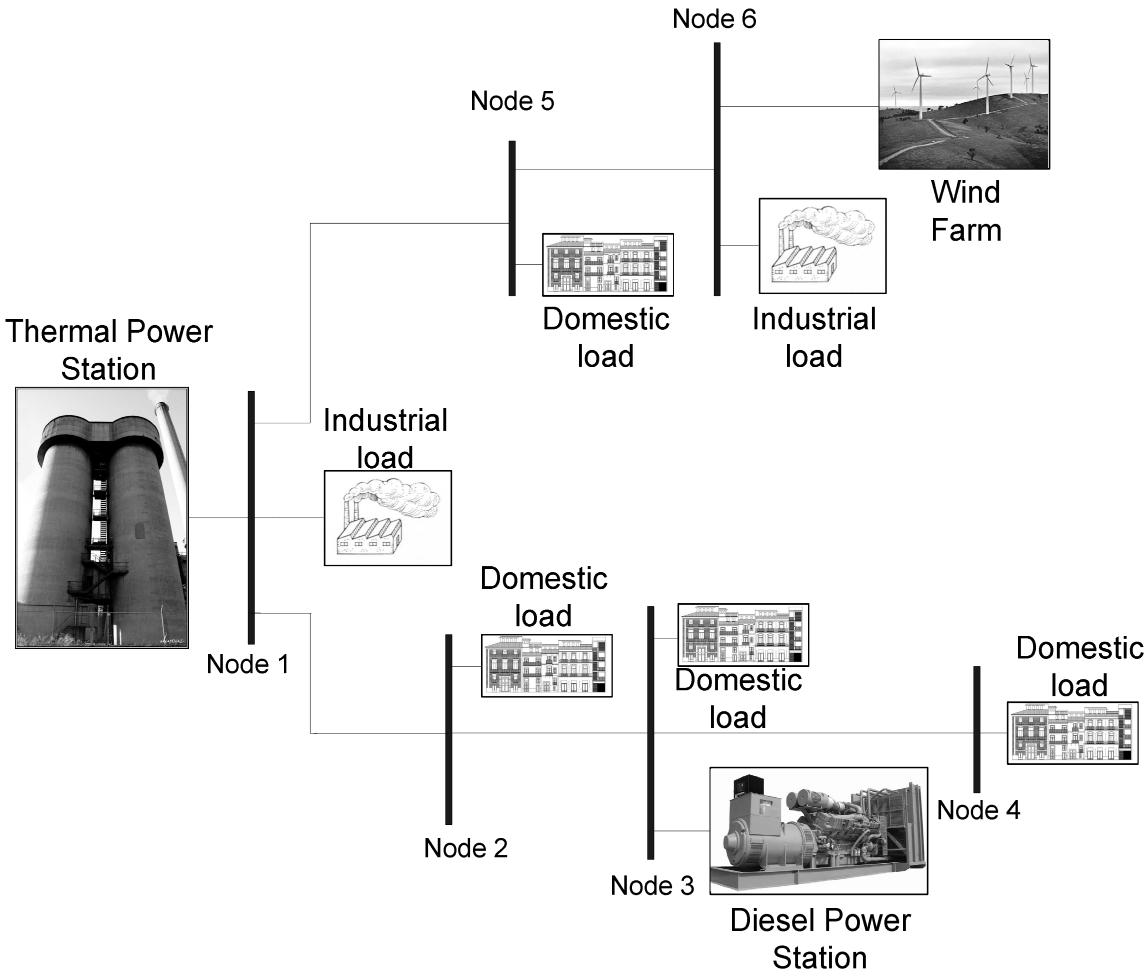

Figure 55: Proposed scenario

The models proposed in chapter 3 are used to simulate this scenario. The most important characteristic of diesel and reheat steam turbines are shown in Table 7 and Table 8. Table 5 shows minimum and maximum load values in the different nodes of the power system. Table 6 shows the line impedances between the different nodes. These values are implemented in the simulation tool proposed in chapter 3.

TABLE 5
MAXIMUM AND MINIMUM LOAD IN THE DIFFERENT NODES

	Minimum load (MW)	Maximum load (MW)
Node 1	10.0	20.7
Node 2	4.0	7.5
Node 3	4.5	8.5
Node 4	1.4	2.9
Node 5	3.0	4.7
Node 6	5.4	10.8

TABLE 6
LINE IMPEDANCES IN PU

Line	R (pu)	X (pu)
1-2	0,01963	0,05475
2-3	0,03419	0,14463
3-4	0,08555	0,29528
1-5	0,09778	0,27271
5-6	0,07111	0,19834

TABLE 7
REHEAT STEAM TURBINE PARAMETERS

P_{nom}	H	R	T_{RH}	T_{CH}	F_{HP}	F_{LP}	T_G
30 MW	3.36 s	0.04	7.0 s	0.3 s	0.7	0.3	0.02 s

TABLE 8
DIESEL GENERATOR PARAMETERS

P_{nom}	H	R	T_{1d}	T_{2d}	T_{3d}	T_G
15 MW	2.08 s	0.05	0.09 s	5.56 s	7.52 s	0.02 s

5.3.3. Simulation results

Figure 56 shows the response of the system in the proposed scenario for a sudden disconnection of the diesel generator.

The use of an Ultracaps based ESS in the face of this event will be analyzed. The maximum frequency deviation accepted in the operation of the Spanish electrical grid is 0.5Hz.

Below this value starts the emergency operation (P.O.-1.6), in which several devices are disconnected from the grid.

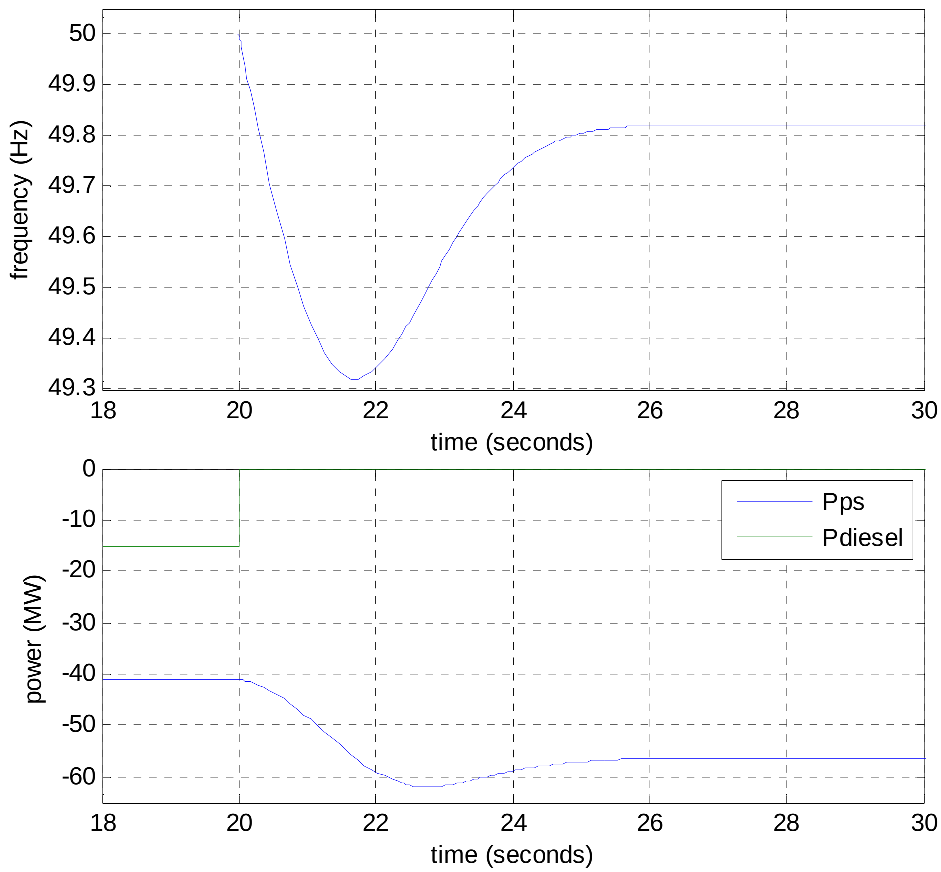

Figure 56: Frequency response in the face of the disconnection of the generator.

Different options for the power response curve of the Ultracaps ESS are compared. For a trapezoidal response curve the design of the Power Conversion System for the Ultracaps ESS will depend on the delay time (t_d), the rising time (t_r), the falling time (t_f) and the full power supply time (t_p) of the system or the power supply variation (ΔP). Other option for the response curve is to emulate the response of conventional generators and supply the stored energy depending on the derivate of the frequency deviation. This response may reduce the needed energy reserve in the Ultracaps.

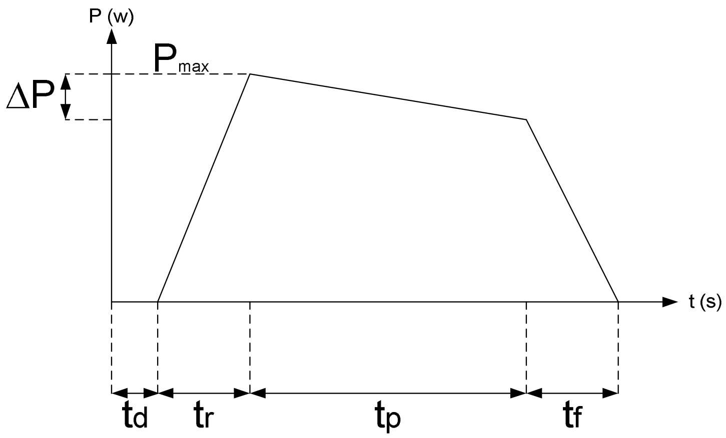

Figure 57: Trapezoidal power response of an Ultracaps ESS

Regarding Figure 58 it can be deduced that the power supply should last between 1 and 2 seconds. For a load disconnection of 15MW the frequency deviation is 0.68Hz, maintaining the same relation, the ESS should be sized for a maximum peak around 4MW. Several simulations with different power responses for the Ultracaps ESS have been carried out to define the impact of the different parameters that define the trapezoidal power curve.

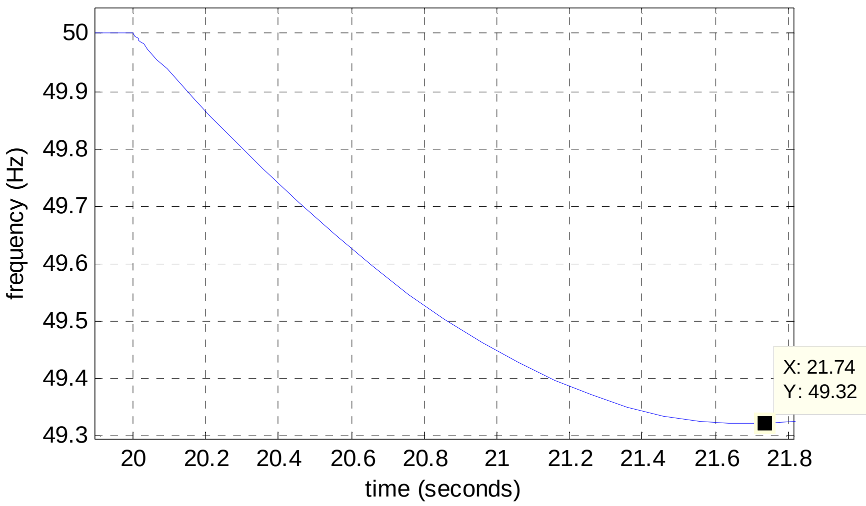

Figure 58: Frequencies drop in the face of the disconnection of the generator

The following simulations show the effect of the power supply variation for these delay and rising times. The inertial response will be compared for these last restrictions in the signal.

TABLE 9
RESULTS OF COMPARATIVE SIMULATIONS

td (ms)	tr (ms)	tp (ms)	tf (ms)	Pmax (kW)	ΔP (kW)	fmin (Hz)
100	100	2000	100	4000	0	49,57
200	100	2000	100	4000	0	49,55
300	100	2000	100	4000	0	49,54
400	100	2000	100	4000	0	49,52
500	100	2000	100	4000	0	49,5
100	100	2000	100	4000	0	49,57
100	200	1900	200	4000	0	49,56
100	300	1800	300	4000	0	49,55
100	400	1700	400	4000	0	49,55
100	500	1600	500	4000	0	49,54
100	100	2000	100	4000	0	49,57
100	100	2000	100	4000	1000	49,56
100	100	2000	100	4000	2000	49,54
100	100	2000	100	4000	3000	49,52

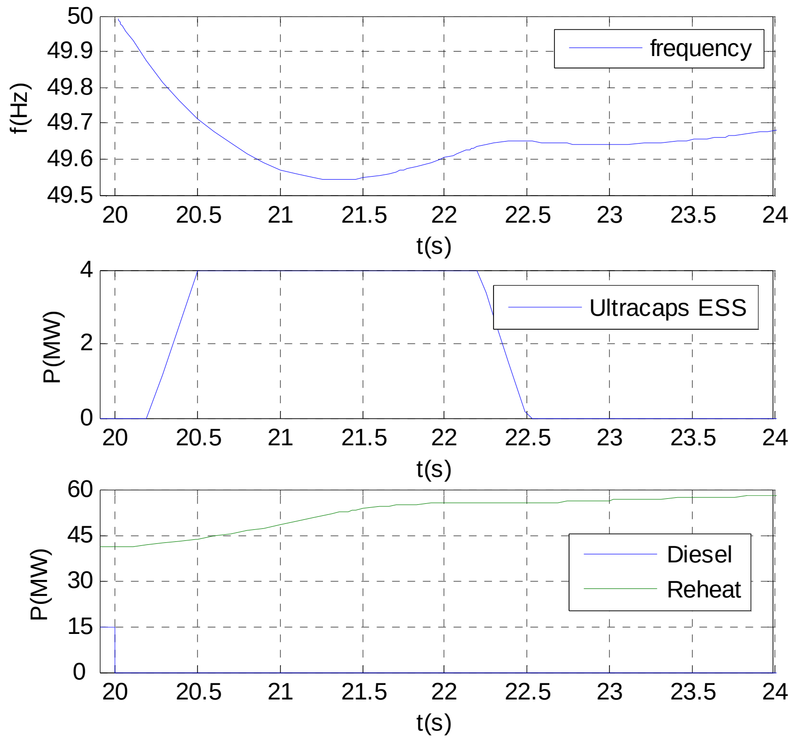

Figure 59: Frequency response, using an Ultracaps ESS for the attenuation of the event td=200ms, tr=300ms, tp=1.7s, tf=300ms and ΔP=0.

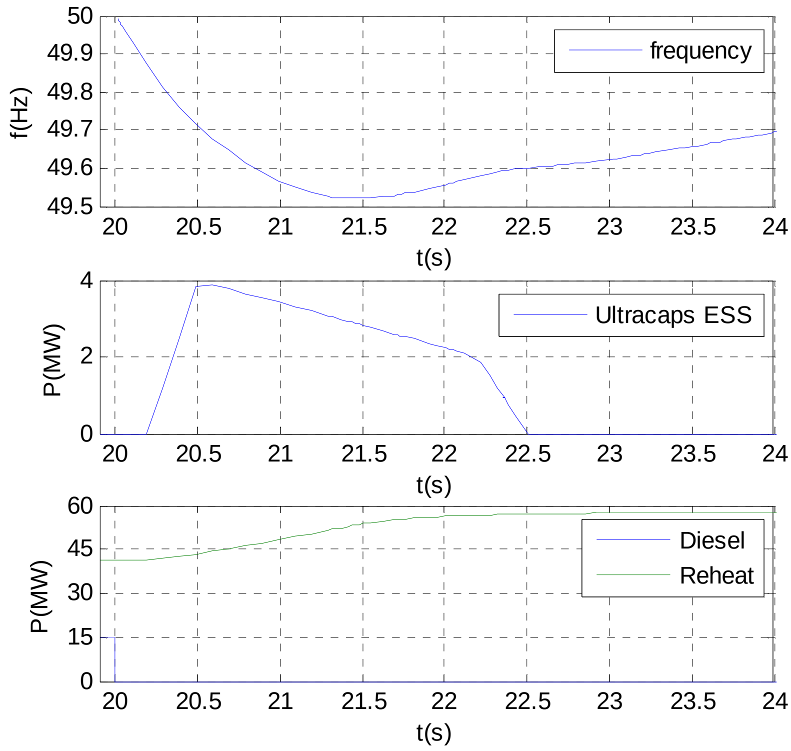

Figure 60: Frequency response, using an Ultracaps ESS for the attenuation of the event td=200ms, tr=300ms, tp=1.7s, tf=300ms and ΔP=2MW.

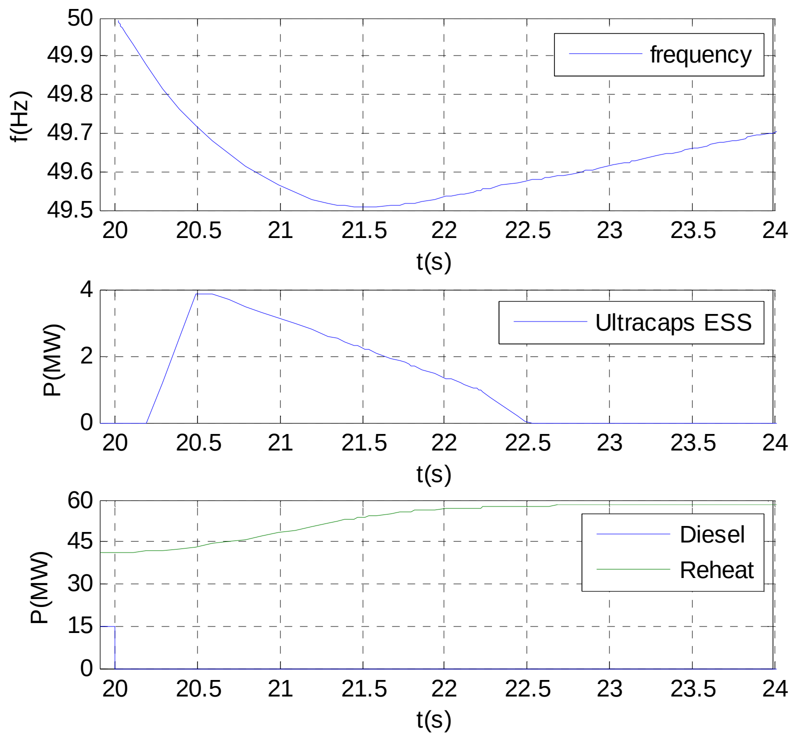

Figure 61: Frequency response, using an Ultracaps ESS for the attenuation of the event td=200ms, tr=300ms, tp=1.7s, tf=300ms and ΔP=3MW.

These last simulations show (Figure 59, Figure 60, Figure 61) that reducing the power supply after the first peak of power should not be a problem, because the most important is to supply the peak power in the precise instant and maintain a certain supply during several milliseconds until the rest of generators respond.

The comparison between inertial and trapezoidal response show that the inertial response is slightly worse than the trapezoidal but it needs less energy. In fact the inertial response meets better the need of power. The comparison between the trapezoidal response and inertial response is shown in Figure 10. The same restrictions were considered: 200ms time delay and 300ms for rising and falling time. The inertial response is shown to emulate different inertias. The bigger is the inertia more similar is the inertial response to trapezoidal.

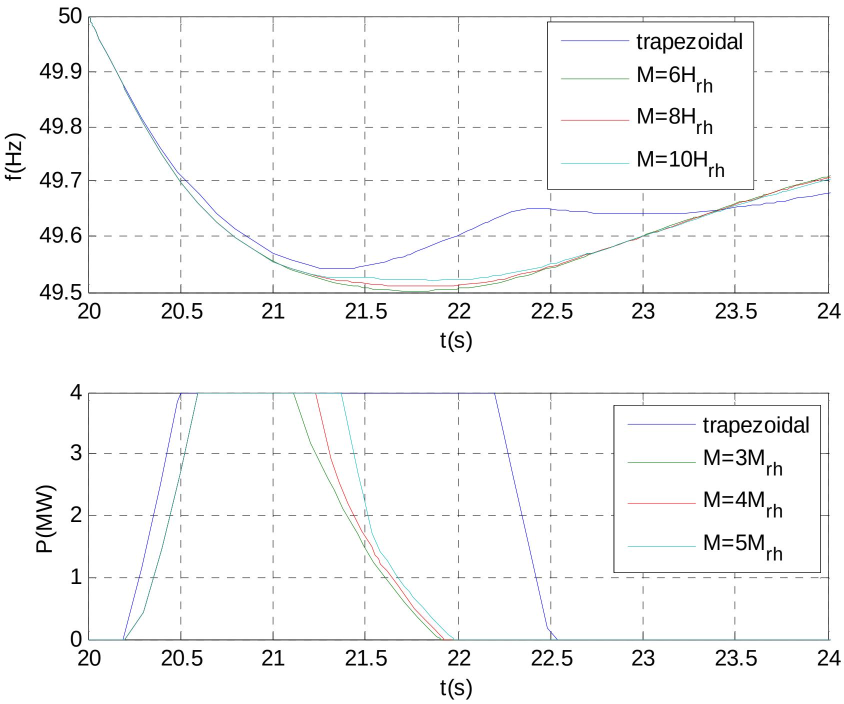

Figure 62: Comparison between inertial and trapezoidal response for a time delay of 200ms and a minimum rising time of 300ms

All these simulations were carried out for specific conditions in a specific power system. In other conditions the results would be different. Anyway in weak power systems where the disconnection of one generator may cause a serious frequency deviation the rest of the generators will not respond until it might be too late. In these conditions a very fast power supply reduces the frequency deviation. The most important condition is to supply the required power before the frequency fall under security levels. The ESS should maintain a certain level of power supply until the rest of the generators compensate the power deviation.

The market available Ultracaps modules may supply a constant peak current during 1 or 2 seconds reducing the voltage to the half up to the total discharge of the capacitors. Regarding this fact the power supply variation should be the half of the peak power, more or less.

5.4. ESS for primary frequency regulation

Load perturbations in completely isolated and relatively small power systems have a considerable effect on the networks frequency. This is due to the fact that the kinetic energy stored in the rotating machines is usually the main source of immediate reserve available in the power system. Thus, a system with low inertia is particularly sensitive to sudden load changes. Furthermore, the rapid output power variations required from thermal units result in cyclic fluctuations in steam pressure and temperature [74]. In the previous section the use of fast response ESSs in the face of large transient frequency deviations has been analyzed. Primary frequency regulation was discussed in chapter 4, in this section the contribution of ESS will be analyzed.

The use of batteries in small power systems to contribute in frequency regulation is analyzed since many years ago [74, 75]. In small power systems batteries are used for the regulation of the voltage and the frequency. Batteries present some limitations for this task that should be taken into account:

- Charge/discharge ratios of the battery: the characteristics of charge/discharge define the charge and discharge methods of the batteries. Most of the batteries (except flow batteries) should be charged at constant voltage and current. The discharge is also limited in a range of current.
- Life cycle of the battery depending on the depth of discharges: the life cycle of most of the batteries gets drastically reduced out of some limits of depth of

discharge. Lead-acid batteries may work between the 50% and the 90% of the charge, Li-ion batteries may work between the 20% and the 90%, flow batteries and NaS batteries may work almost with any depth of discharge.

- Power output: the maximum power output limits the maximum frequency deviation that may be restored.
- Energy Storage Capacity: the total stored energy defines the capacity of charge and discharge.

5.4.1. Analytical study of the problem

The steady state frequency deviation in a power system is given by equation (5. 8). The load variation should be compensated by the generators with primary regulation. The generators connected to the system respond to frequency deviations in real time with the droop characteristic. These generators vary their speed during the primary frequency regulation. Batteries may contribute in the primary frequency regulation, reducing the steady state deviation of frequency.

$$\Delta f_{ss} = -\frac{\Delta P_L}{1/R_{eq}} \tag{5. 8}$$

The Battery Energy Storage System (BESS) should be designed to reduce the steady state frequency deviation. The BESS will act following a droop characteristic, absorbing the maximum power for the maximum frequency value and supplying maximum power for the minimum frequency value. The bigger is the battery power output, the smaller is the steady state frequency deviation.

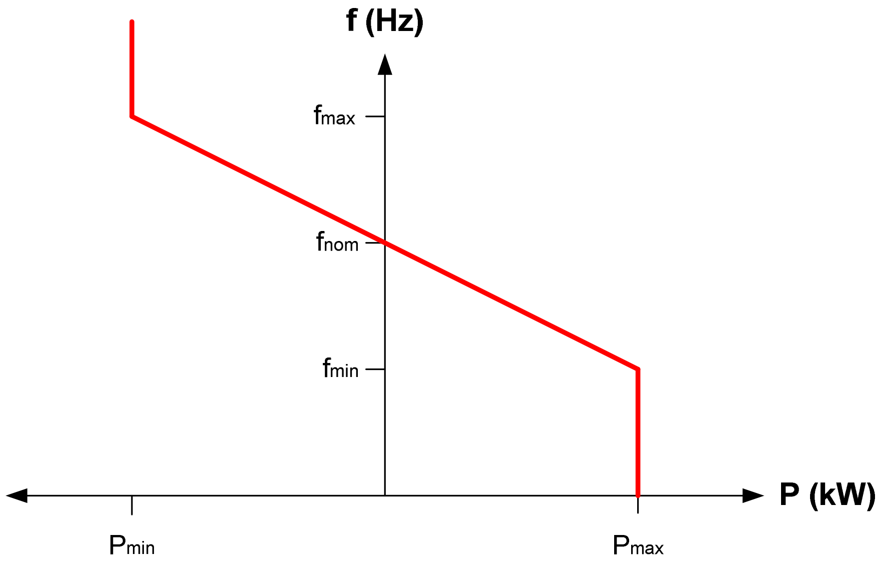

Figure 63: Droop characteristic of a BESS for frequency regulation

Thus the sizing criteria for a Battery Energy Storage System for frequency regulation depend on the maximum steady state frequency deviation. From equations (4. 14), (4. 15) and (5. 8), the relation in p.u. is given by the following equations:

$$\Delta f_{ss\,MAX} = \frac{\Delta P_{L\,MAX}}{1/R_{eq}} = \frac{\Delta P_{L\,MAX}}{\frac{1}{R_{eq}} + \frac{1}{R_{BESS}}} \quad (5.\ 9)$$

$$R_{BESS} = \frac{1}{\left(\frac{\Delta P_{L\,MAX}}{\Delta f_{ss\,MAX}} - \frac{1}{R_{eq}} \right)} \quad (5.\ 10)$$

$$P_{BESS} = \frac{f_{MAX}}{R_{BESS}} \quad (5.\ 11)$$

The energy storage capacity of the BESS should be sized to ensure enough energy for frequency regulation. With the proposed droop characteristic the batteries should supply power until the frequency is restored, so the storage capacity depends on the secondary frequency regulation of the system. The secondary regulation acts after a delay (t_{sec}), during this delay the BESS will supply constant power. Considering a lineal secondary regulation the BESS power supply will be reduced lineally following the behavior of the frequency, until the frequency is restored (t_{res}). From these considerations the necessary energy storage capacity to restore the largest deviations is obtained.

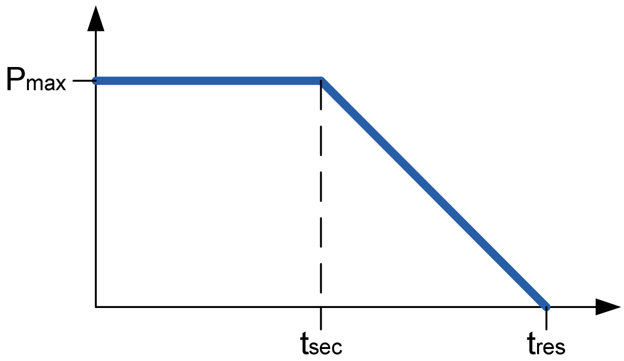

Figure 64: Power supply of a BESS for the primary frequency regulation of the maximum deviation.

$$E_{BESS} = P_{\max} \cdot t_{\sec} + P_{\max} \cdot \left(\frac{t_{res} - t_{\sec}}{2} \right) \tag{5. 12}$$

Common load demand profiles have normally a maximum consumption in the evening and a minimum consumption in the early morning. The BESS will overall supply power to control the frequency from the minimum to the maximum load demand and absorb from the maximum to the minimum. Hence the energy storage capacity should be enough to supply or absorb energy from the demand peak to the valley and vice versa. In equation (5. 12) the energy to restore the maximum frequency deviation is calculated. To calculate the total energy need for frequency regulation the total power difference should be taken into account and also the share of power with the spinning reserve defined by the droop characteristics. Substituting P_{max} by the total power share of the BESS for frequency regulation an approximation to the total need of energy is obtained:

$$E_{BESS} = \frac{R_{BESS}}{R_{eq} + R_{BESS}} \left(P_{peak} - P_{valley} \right) \cdot \left(t_{\sec} + \left(\frac{t_{res} - t_{\sec}}{2} \right) \right) \tag{5. 13}$$

Where P_{max} is the peak load demand and P_{valley} is the valley load demand.

The sizing criteria may vary, if the BESS should participate in the secondary frequency regulation, the BESS will need more storage capacity and higher nominal power. The droop characteristic of Figure 63 should be variable. The set point of the droop characteristic is selected depending on the share of power in the system. In each case the grid operator should define the power contribution of the battery for different time slots during one day.

5.4.2. Scenario for the case study

The scenario for this case study will be the same 6 nodes grid of the previous subchapter. Considering the same generation units and installed load, the difference with the previous subchapter consists of analyzing the load variability instead of the disconnection of a generator.

The load demand curve given for a certain day in the Spanish electrical grid, with 10 minutes values, defines the load demand curve used for this analysis. In the proposed scenario for a maximum load demand of 40.5MW the installed power in conventional generators is 75MW, 2 reheat steam turbines and one diesel generator. A 15 MW wind farm is also connected to the same power system.

The characteristics of the different generators are shown in Table 10 and Table 11:

TABLE 10
REHEAT STEAM TURBINE PARAMETERS

P_{nom}	H	R	T_{RH}	T_{CH}	F_{HP}	F_{LP}	T_G
30 MW	3.36 s	%10	7.0 s	0.3 s	0.7	0.3	0.02 s

TABLE 11
DIESEL GENERATOR PARAMETERS

P_{nom}	H	R	T_{1d}	T_{2d}	T_{3d}	T_G
15 MW	2.08 s	%10	7.0 s	0.3 s	0.7	0.02 s

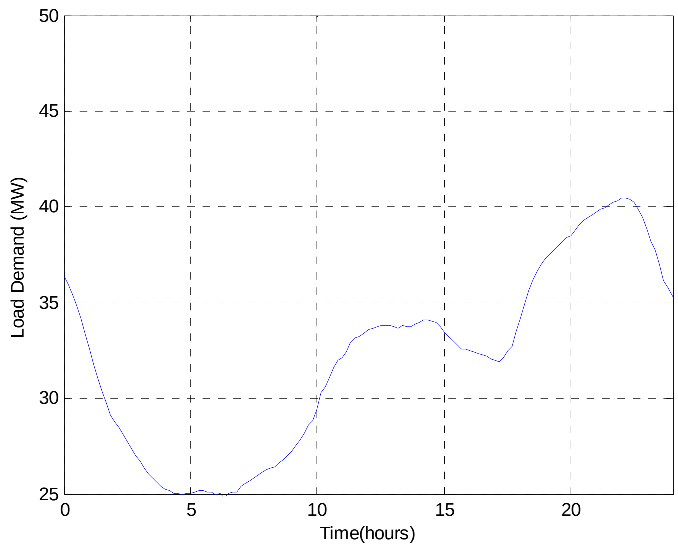

Figure 65: Load demand during 24 hours.

The sizing of the BESS should respond to the primary, to obtain a maximum steady state frequency deviation of 0.1Hz, considering that the maximum instantaneous load deviation is 2MW and the equivalent droop characteristic (R_{eq}) of the system is 5%. Following the previously defined sizing criteria:

$$R_{BESS} = \frac{1}{\left(\frac{2MW/S_{BASE}}{0.1Hz/f_{BASE}} - \frac{1}{5\%}\right)} = \frac{1}{\left(\frac{2MW/20MW}{0.1Hz/50Hz} - \frac{1}{5\%}\right)} = 3.33\% \quad (5.14)$$

$$P_{BESS} = \frac{\Delta f_{MAX}}{R_{BESS}} = \frac{0.1/f_{BASE}}{3.33\%} = 0.06pu \rightarrow 1.2MW \quad (5.15)$$

The Energy Storage Capacity is sized following the previously defined criteria. The secondary control action has a delay of t_{sec}=60 seconds and it may need up to t_{res}= 2 minute to restore the frequency from the maximum deviation. The peak load demand is P_{peak}=40.5MW and the valley load demand is P_{valley}=25MW. The maximum Energy Storage Capacity needed for the primary regulation is:

$$E_{BESS} = \frac{0.0333}{0.05+0.0333}(40.5-25)\cdot 10^6 \cdot \left(60 + \frac{180-60}{2}\right) = 744000kJ = 206.66kWh \quad (5.16)$$

5.4.3. Simulation results

The design criteria proposed to improve the primary frequency regulation in a weak power system has been analyzed at this point. The performance of the system has been verified in simulation. The performance of the power system without the BESS is shown in the following graphs. These graphs show that the frequency deviation without any support system is quite large. The frequency deviation is larger than 0.2Hz in many cases and the restoration of the frequency to the nominal value takes long by the secondary frequency regulation.

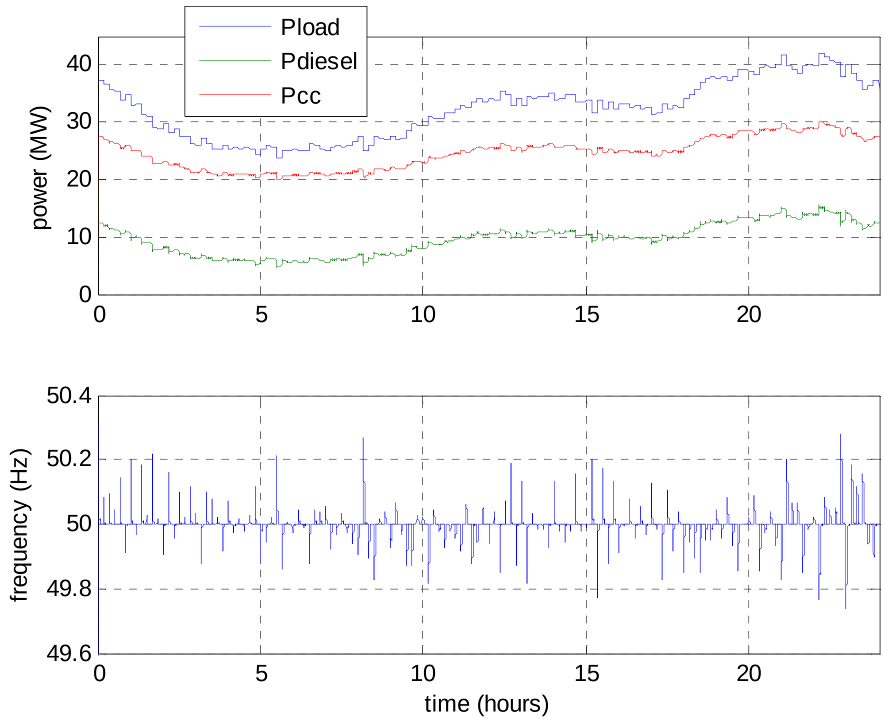

Figure 66: 24 hour simulation of the proposed system without BESS

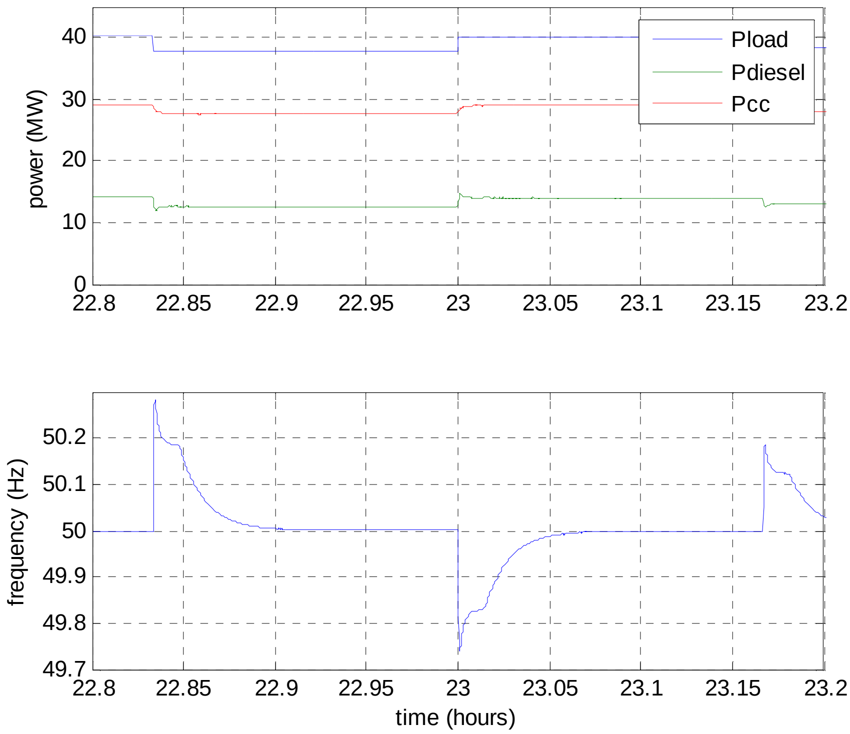

Figure 67: system behavior for the largest load deviations

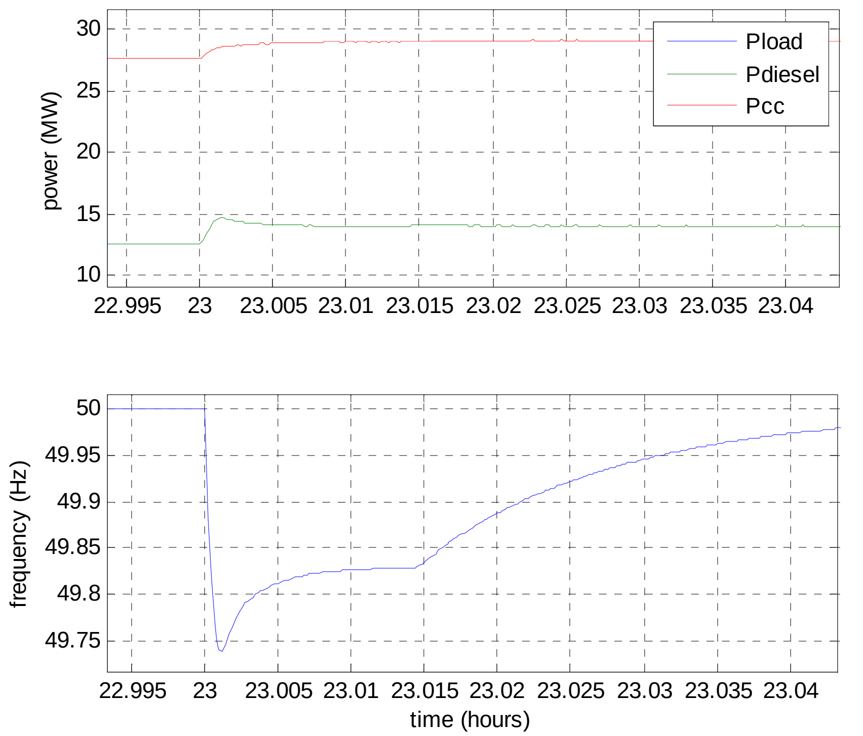

Figure 68: primary and secondary control actions

The same power system is also simulated with a BESS of 1.2MW and 100kWh. In the same scenario the frequency deviation has been clearly reduced, not only in the stationary deviation (which was the aim of the BESS) but also the transient deviations, because the BESS works as an extra generator.

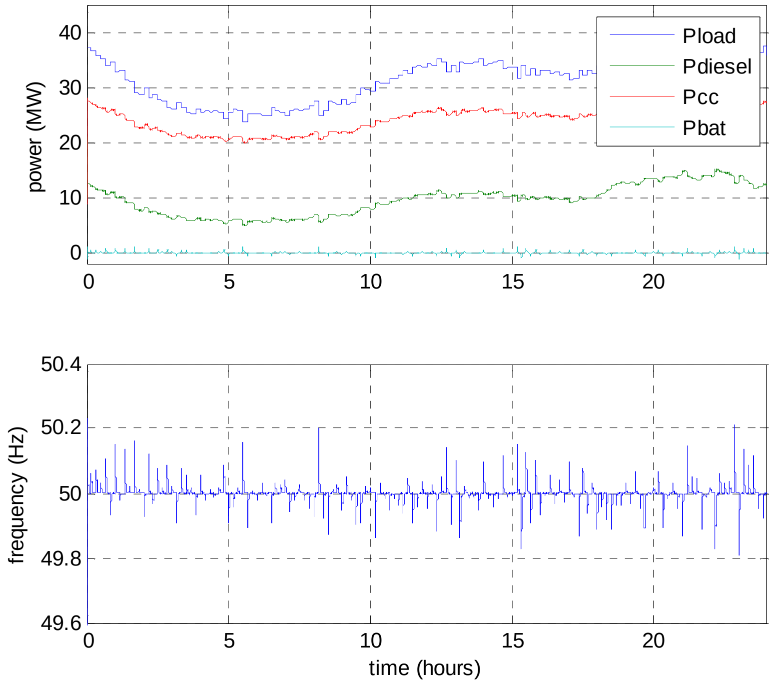

Figure 69: 24 hour simulation of the proposed system with BESS

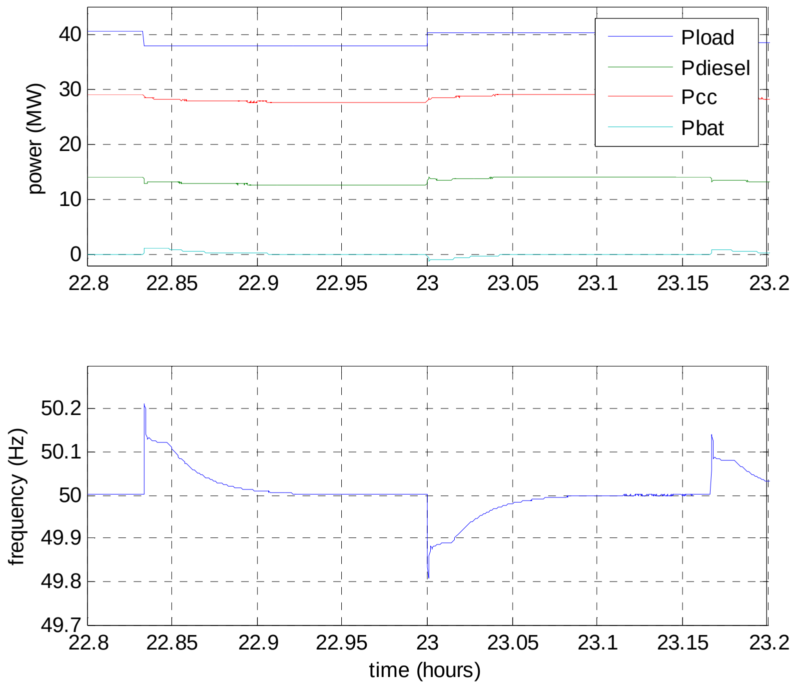

Figure 70: system behavior for the largest load deviations

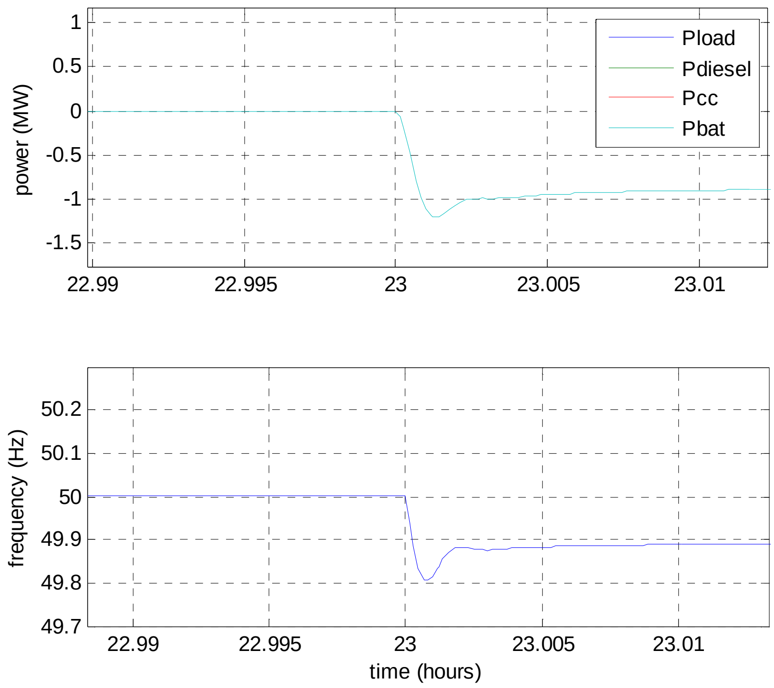

Figure 71: primary control action

5.5. Conclusions

In this chapter it has been demonstrated how the integration of DG in weak electrical networks can be maximized introducing active devices in the MV/LV substation. It has been presented the concept of an Active MV/LV Substation, integrating active devices as: OLTC, STATCOM with Energy Storage and Dump-loads. It has been demonstrated that the control of the voltage level at the PCC is possible monitoring only the local signals at the substation, and with an adequate control/operation strategy of these active devices. An operation and control strategy for the Active Substation has been presented and the performance in a weak grid has been verified by temporal simulations. Active Substations permit to maximize the penetration of DG in weak nodes, in which the voltage stability restrictions limit the installed DG power.

The use of fast response ESSs (Flywheel, SMES, Ultracaps…) to attenuate transient frequency deviations in weak power systems with low inertia was analyzed and it was demonstrated as a suitable solution. The tripping of a generator in these grids may provoke a large frequency deviation in a first instant. Their fast response in the face of power disturbances make Ultracaps one of the best solutions for transient frequency deviations that can be restored later with the control response of the electrical system. This application is very suitable for insular grids with high penetration of renewable energies, because the installation of more generation units to assure the control of the frequency may be avoided. Different power supply curves for Ultracaps ESS have been analyzed giving some constraints for the design of this type of applications. A realistic ESS might take about several milliseconds to supply the maximum power and reduce proportionally this peak power until the total discharge of the system. Load shedding may be avoided by this solution when it is provoked by transient disturbances. The power supplied by the ESS maintains the frequency within accepted limits and permits to start new generators to substitute the generation unit that has tripped.

Battery ESS has been analyzed as a solution for the primary frequency regulation. The use of batteries may avoid the installation of new generators for this purpose. The response of Battery ESS for primary frequency regulation has been demonstrated in simulation as a suitable solution. The frequency deviations are a consequence of load deviations and the average value of load deviations in one day is almost zero, so ESS are the best solution for primary frequency regulation from an energy performance point of view. Furthermore the use of ESS will reduce the CO2 emissions, because the use of conventional generators is avoided.

This chapter focused on the use of different storage technologies to improve the behavior of weak electrical grids, like rural networks (voltage stability problem) or small power systems (frequency regulation problem). A real technical solution to apply the improvements proposed in this chapter will be discussed in chapter 7.

Chapter 6

Energy Storage Systems for Energy Management applications

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6. Energy Storage Systems for Energy Management applications

6.1. Introduction

The variability of renewable energy sources, such as Wind and Solar energy, is their main handicap. The unpredictable and variable nature of these energy resources limits drastically their capacity to supply the energy required in the electricity market.

An application to improve the integration of renewable energies is proposed at this chapter. The use of Energy Storage Systems to control the variable nature of wind energy is analyzed. The use of batteries may convert wind farms into controllable and even predictable energy resources adapting the energy production to the needs of the grid operator. This application might be compatible with the grid support applications analyzed in the previous chapter.

6.2. ESS for Wind Power dispatch

Historically one of the main problems of electricity generation is the necessity to meet instantaneously the electricity demand. Due to the impossibility to store large amounts of electricity the electric power production should be sized to meet the peak demand. In this way the relation between power production capacity and produced power is very low, around 40-50%.

This low capacity factor of electrical grids is turning lower with the impact of renewable energies, such as solar and wind energy. Many times these renewable resources produce their peak power when the consumption is very low, while sometimes there is not any renewable power during peak consumption periods. By storing energy from variable resources, such as wind and solar power, electricity storage could provide firm generation from these units, allow the produced energy to be used more efficiently [7, 8].

The impact of load leveling on reducing transmission and distribution (T&D) losses it has been analyzed in recent years [76], these studies show that the capture of renewable production to deliver when transmission capacity is available, using electricity storage systems may improve the transmission capacity factor for renewable sources.

The storage and latter delivery of renewable energy can be a very valuable solution in order to meet the demand of a certain area with the power consumption of this area. In this way the renewable may be fully consumed reducing the use of fossil fuels and the power transmission losses are reduced because the power is consumed on site.

Furthermore the power constancy of a wind farm can be a very interesting issue for grid operators, since uncertainties are reduced in order to plan the power production. Grid operators should assure several ancillary services and safe, secure and reliable operation of the interconnected power system [77]. In this way the constant power delivery of wind farms help on the control of frequency, reducing the necessary power reserve in each moment. The primary power reserve is the reserve of generators to respond in the face of power variations, the need of this reserve increases due to the variability of wind power. In this context the owners of wind farms can negotiate a special contract if they are able to predict the power delivery in advance.

The specification of an operation algorithm for a grid manager for weak electrical grids, with high penetration of wind energy is proposed at this chapter. The aims of the grid manager are the reduction of the primary power reserve and the optimal performance of the conventional generators using Battery Energy Storage Systems (BESS) in parallel to a wind farm, in order to reduce the uncertainty due to wind power variation.

Depending on the prediction of wind and load demand the system manager will send references to the different generators and BESS every 10 minutes. The BESS will be controlled to absorb wind power variations and estimation errors. The required control algorithm in order to achieve this purpose will be designed.

6.2.1. Scenario for the case study

A weak simplified power system is analyzed with a single consumption node and several generation nodes, in order to analyze the contribution of a battery in parallel to a wind farm to reduce the primary power reserve. The power generation is composed by a main reheat steam power station, several diesel generators and a wind farm. The reheat steam power station has a nominal power of 10MW, the diesel generators have 10MW and the wind farm has 10MW of nominal power. A BESS is in parallel to the wind farm.

In this scenario conventional (reheat steam and diesel) generators are able to meet the maximum power demand, in this way the power supply is assured even during periods without wind power production.

A simplified electrical grid will be considered where all the elements are connected to the same node through impedance representing a line. The wind farm and BESS work as power station able to predict a constant power delivery for the next hour. In this way the primary power reserve is reduced to the uncertainty of the power demand.

In this scenario the wind farm operator sends the information about the next hour power production of the wind farm and the grid operator sets the reference power for the conventional power sources, the primary power reserve of these generators will meet the difference between the real and predicted power demand.

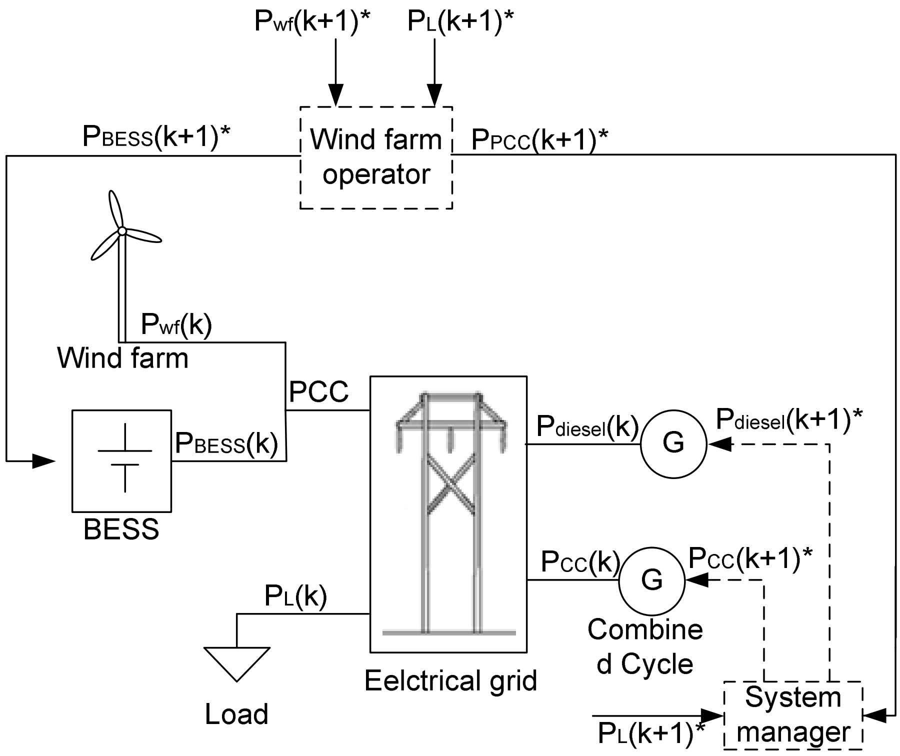

Figure 72: Scenario proposed for the study

Real load and wind profiles are generated to simulate the system, while forecasted load and wind profiles are used as predicted data for the System Manager.

For the simulations was chosen the wind speed data, measured in a wind farm located on Oiz Mountain, Bizkaia, this data is available in [78]. Ten minute mean wind speed data is given, as well as the standard deviation, the maximum speed and the minimum speed during these 10 minutes. This data has been used to generate a wind speed profile and therefore the Wind Energy generation.

The forecasted wind profile is quite precise, because for ten minutes predictions a mean error of 0.198 m/s and a standard deviation of 0.181 m/s can be considered [79]. The forecasted wind profile is generated adding a random error with this standard distribution to the real mean value.

A proportional value of the load demand curve given for a certain day in the Spanish electrical grid, with 10 minutes values, is used as a forecasted load profile. The real load profile is proportional to this load demand, but adding two different standard deviations. On the one hand the common deviation due to the connection and disconnection of domestic load with a standard deviation of 10kW, on the other hand the deviation due to industrial loads or mistakes in other considerations with a standard deviation of 300kW.

6.2.2. Operation strategy

As the utilities must always ensure the balance between generation and consumption they have to hold power reserve for unexpected load ramps, unit breakdowns and lack of primary energy. Due to technical and economic restraints this power reserve is divided into primary, secondary, and long-term reserve according to its activation time [80]. In a power system with high penetration of wind power the primary power reserve should be sized to respond the deviations of load consumption and wind power generation. In a small power system these deviations can be a very important part of the total installed power. This primary reserve should be fast to avoid large frequency deviations. Using a battery to absorb the variations of wind power the primary power reserve can be reduced to respond only to load deviations.

Figure 73 shows the simulation of the system with and without battery. In the first graph the wind power prediction and the real wind profile are compared. In the second the real and forecasted load demands. While third and fourth graphs show the sharing of power generation with and without BESS working in parallel to the wind farm. These graphs show that using a battery can be reduced the primary power reserve. But also that absorbing the power variations by the battery the performance of the different generators is improved working most of the time with nominal power. This makes the regulation of the system more predictable.

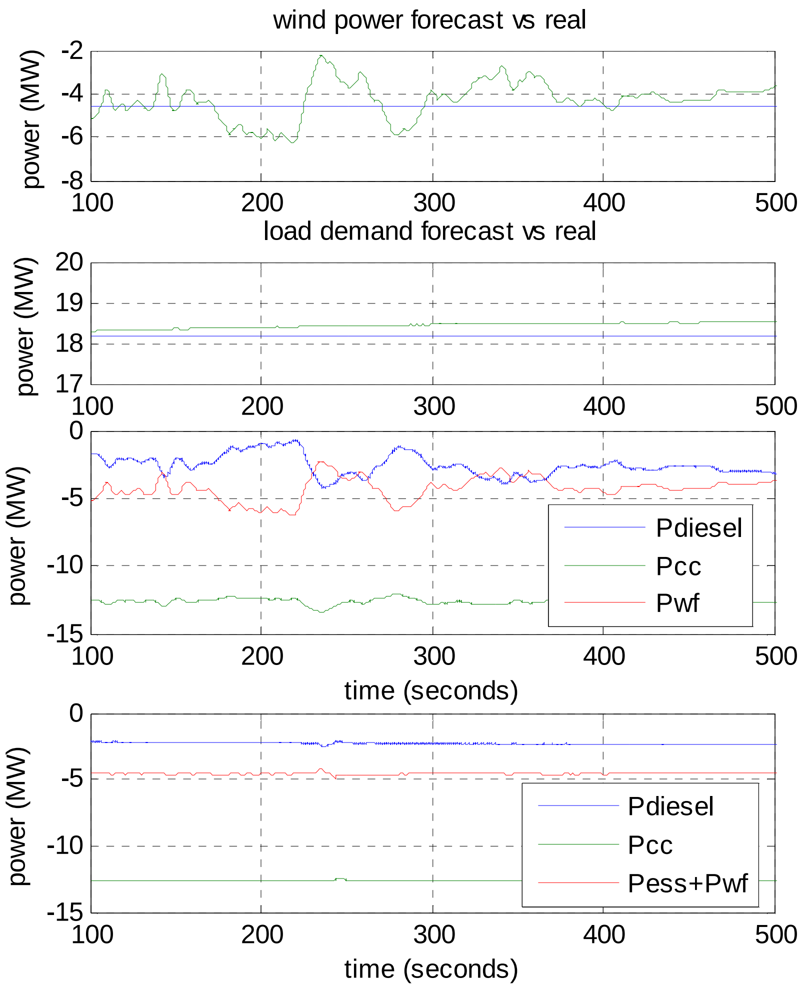

Figure 73: Comparison of the system behavior

The operation strategy should meet the power demand instantaneously using the active control devices of the system. In this case they are the BESS, the reheat steam power plant and the diesel power plant. Using ten minute predictions of load demand and forecasted wind profile the system manager sets the control references for the diesel and combined cycle power plants for the next period (10 minutes) k+1.

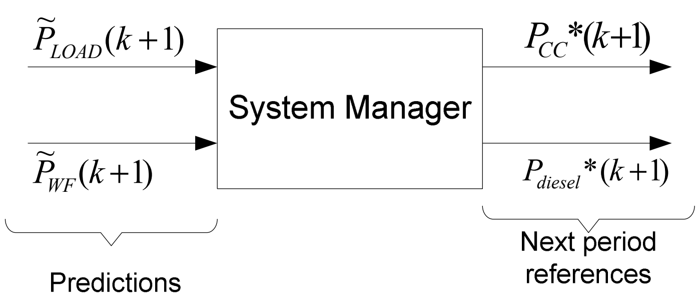

Figure 74: System manager

$$P_{CC}*(k+1) = -\widetilde{P}_{LOAD}(k+1) - \widetilde{P}_{WF}(k+1) \quad (6.\ 1)$$

$$P_{diesel}*(k+1) = -\widetilde{P}_{LOAD}(k+1) - \widetilde{P}_{WF}(k+1) - P_{CC}*(k+1) \quad (6.\ 2)$$

During each period the diesel power station changes its load reference in order to keep constant the frequency.

$$P_{diesel}*(k) = -\frac{K_I}{s} \cdot \frac{\Delta f}{R} \quad (6.\ 3)$$

The operation of the BESS aims to control the active power output in order to keep it constant during each period of ten minutes. The output power of the BESS is controlled in order to meet the power demand instantaneously. The ten minute period predictions permit to the BESS to have enough reserve power and energy to respond to the most of the deviations between the predicted and real wind power.

6.2.3. Sizing of the BESS

The use of batteries in parallel to a wind farm requires a realistic sizing. The sizing of the BESS should take into account two main variables, on the one hand the variability of the wind power and the load demand, on the other hand the investment. In this way the BESS should be sized, as small as possible, to respond to the maximum of deviations between load/generation.

In the proposed application the facility composed by the wind farm and the BESS ensures certain power during ten minute periods. In this scenario the BESS should absorb or supply the difference between the wind power forecast and real generation every ten minutes. The sizing of the BESS should be calculated in order to fulfill this requirement as many times as possible.

The sizing of a BESS depending on the wind power forecast uncertainty is analyzed in [81]. An analysis related to cost-benefit and wind farm dispatch is given by [82]. In the first publication authors propose a method to calculate the unserved energy depending on the sizing of the BESS, in the second publication authors propose certain sizing based on the reduction of unserved energy but also the economical costs of the BESS.

In this case the instantaneous variation of the load is under 100kW while the wind power variation can vary from maximum power production to zero in few seconds. Most of the instantaneous deviations of wind power are between ±10% of the nominal power, so using a battery of this size most of the disturbance produced by the wind farm may be avoided. For the nominal power around 20 MW a 2 MW battery is enough.

With good wind forecast the average deviation between real and predicted wind power is small [83, 84]. 500 kWh would be enough because the wind predictions are given every 10 minutes. Considering small deviation between wind forecast and real, 15 minutes of power reserve should be enough.

6.2.4. Simulation results

24 hour simulation has been carried out in order to show the behavior of the system. Figure 75 shows 4 hours simulation from 10:00 to 14:00. In the first graph the predicted and real wind power for this period are shown, while in the second the real and predicted load demand profiles are shown. In the third graph are shown the power outputs of the different generators, considering the Wind Farm+BESS as a single generator. The fourth graph shows the State of Charge of the BESS. In this simulation the aim of the BESS is to absorb the variations of wind power.

With the proposed algorithm and precise wind forecast the power supplied by the Wind Farm becomes predictable.

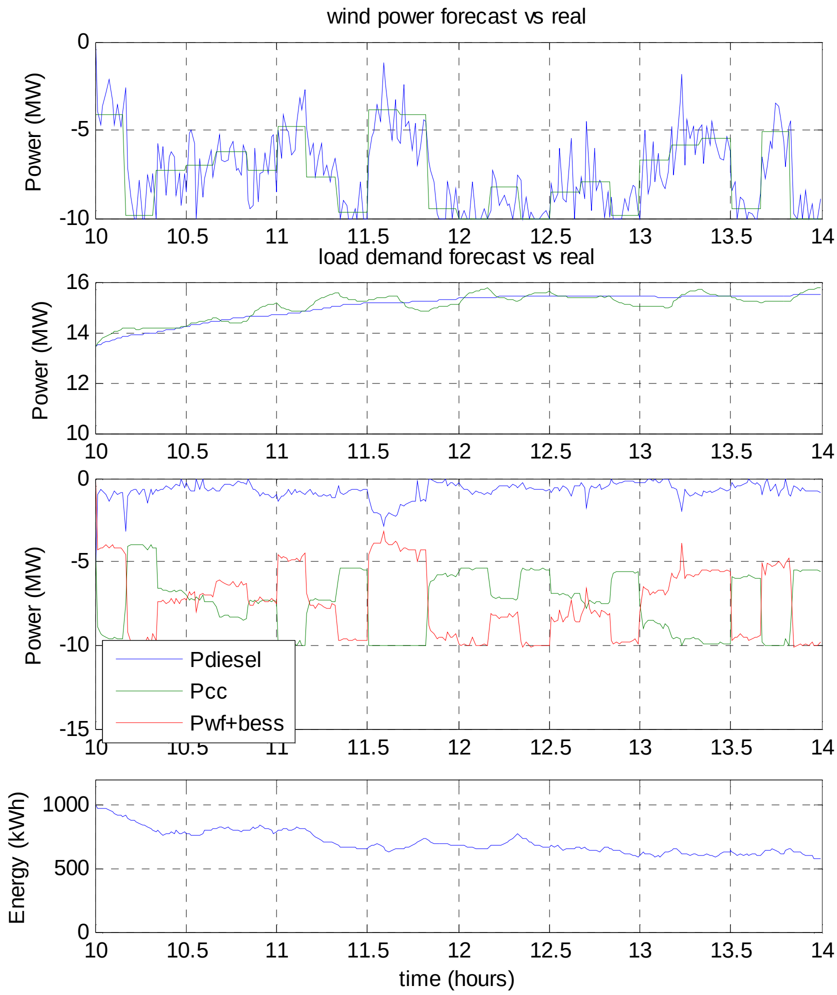

Figure 75: Simulation of the system.

6.3. Chapter conclusions

An intelligent wind farm that may forecast the power production every ten minutes has been proposed at this chapter. This functionality may permit to increase the deployment of wind farms participating on a smart share of the energy generation. The proposed application is a suitable solution to achieve the EU aims of 20% of renewable energy generation.

A predictable power dispatch for wind farms is possible with an adequate sizing of the BESS that will work in parallel to the wind farm. The sizing of the BESS is closely dependent to the wind forecast. With ten minutes predictions the deviation between prediction and reality is low but with worse predictions the size of the BESS would increase and also the costs.

A Wind Farm with a controllable power dispatch and a precise generation forecast will permit to the owner of the Wind Farm negotiate a special price with the Grid Operator. The tertiary regulation of the electrical grid is modified every 10 minutes, a wind farm that may predict the wind power generation for the next 10 minutes period avoids the uncertainty for the Grid Operator in order to set the different references for the regulation of the grid.

Chapter 7

Integral ESS solution for Grid Support applications

7. Integral ESS solution for Grid Support applications

7.1. Introduction

Once Grid Support applications for ESS were analyzed in chapter 5, it is interesting to focus on their design. The aim of this chapter is the design of an Energy Storage System that may respond to the different problems and solutions analyzed in chapter 5.

The common connection topology of ESS is composed by a bidirectional DC/DC boost converter, connected to a DC bus with a bus capacitor, the system is connected to the grid by means of an inverter and depending on the grid voltage it might be necessary a transformer to elevate the voltage.

In the present chapter the connection of a Battery ESS and Ultracaps ESS within a single storage system will be discussed. This combination of different storage technologies is considered here as a Hybrid ESS.

7.2. Energy Storage System design proposal

The design of an ESS is defined by several design constraints. Depending on the power and energy requirements of the application, a storage technology should be chosen. It is also important the connection voltage of the system: depending on the connection to bus more or less batteries or Ultracaps should be connected in series.

7.2.1. Functionalities

In chapter 5 several applications for ESS are analyzed. The design of an ESS that is able to accomplish these applications is proposed at this point. The aim of this ESS is then to cover the following functionalities:

- Restoration of frequency.
- Primary frequency regulation
- Voltage regulation

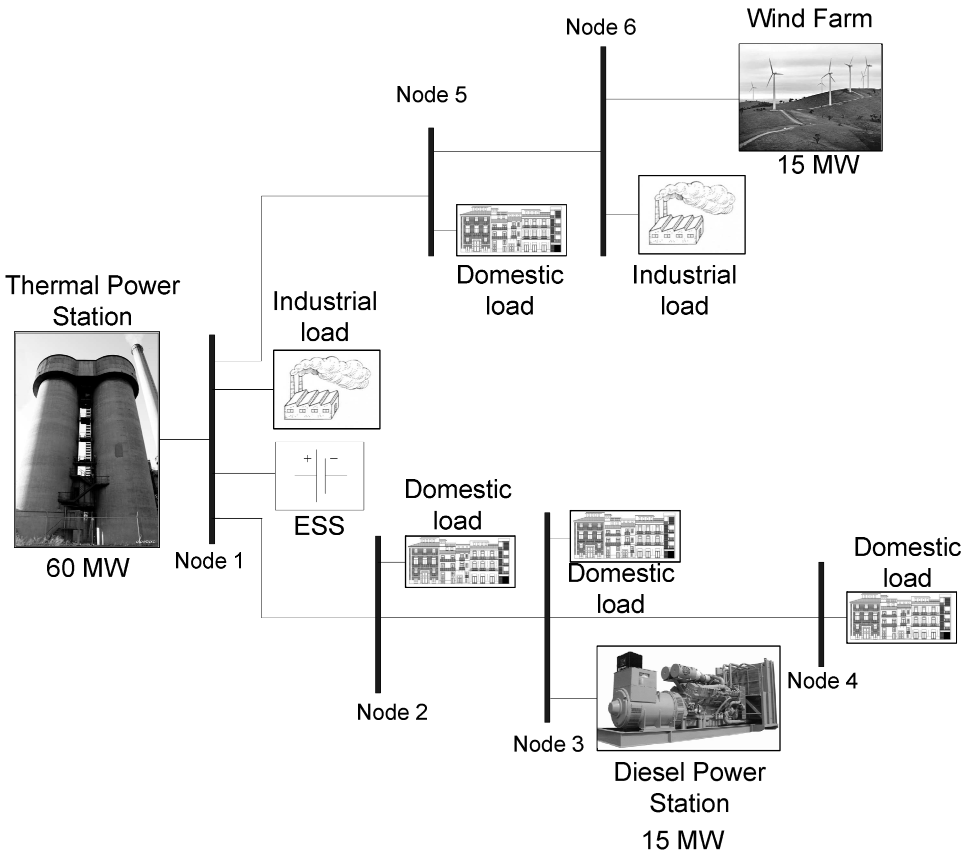

Figure 76: Proposed scenario

From these functionalities active and reactive power specifications and the energy required for the Energy Storage System may be deduced. The scenario of sections 5.3 and 5.4 is considered to size the proposed ESS.

Active power

From the sizing criteria defined in chapter 5 is obtained the nominal active power output of the system. The response to large frequency deviations requires a large initial peak of active power during few seconds, while the primary frequency regulation requires an elevated power supply during few minutes. This action is continuous depending on the variation of the load demand and the renewable generation.

Energy

The response to large frequency deviation last normally few seconds every several days, so the required energy is very low for this application, compared to the required power. The primary frequency regulation is a very frequent application so it requires a certain amount of energy as calculated in section 5.4.

TABLE 12
ACTIVE POWER AND ENERGY REQUIREMENTS OF THE PROPOSED ESS

Application	Active Power	Energy
Frequency restoration	4 MW	2 seconds
Primary frequency regulation	1.2 MW	210 kWh

Reactive power

The reactive power is specified by the voltage regulation, depending on the reactive power compensation to assure the control of the voltage within certain levels. In order to fulfill the specification proposed in subchapter 5.2 the capacity to supply reactive power should be able to control the 10% of the nominal voltage in the PCC of the ESS.

In the proposed scenario the STATCOM of the proposed ESS will be able to supply 5MVAr of reactive power almost all the time, except in the case of the tripping of a generator. This reactive power compensation capacity is far enough to control the voltage in the proposed scenario.

7.2.2. Hybrid Energy Storage System

The proposed ESS has a maximum power output of 5.2 MW and 210kWh of energy storage capacity. In chapter 2 were discussed the properties of the different ESS technologies.

Flywheels and Ultracaps due to their fast response may be the solution for this ESS. Their dynamic is fast enough to respond to the tripping of a generator and it is possible to store 210kWh with these technologies. Even though to store 210kWh with these technologies the power output that may be obtained is much larger than 5.2MW. A lot of power is then unserved. The use of these technologies may be recommended for the restoration of frequency but not for primary frequency regulation. As mentioned in chapter 5 Ultracaps have better Energy Density than Flywheels and as mentioned in chapter 2 this technology has nowadays more development since many manufacturers are working with it. Even so, Ultracaps are considered here as the best solution for this application.

In chapter 2 was discussed that Li-ion batteries may supply a maximum current of 10C, this means that for a power supply of 5.2MW the storage capacity would be at least 520kWh, and 300kWh will be unserved. Furthermore the response of Li-ion batteries is fast but not as fast as Ultracaps or Flywheels. Li-ion batteries may be a very good solution for primary frequency regulation but Ultracaps or Flywheels are better for the frequency restoration application.

The charge/discharge capacities of the rest of the battery technologies are much smaller than Li-ion batteries, so it would suppose a lot of unserved energy storage capacity. Using these technologies more functionalities may be added to the ESS: peak shaving, load leveling… Although for the proposed applications would be enough with Li-ion batteries.

At this point the combination of Ultracaps and Li-ion batteries is proposed to respond to the three applications proposed in chapter 5. The use of different storage technologies connected to the same DC bus is defined here as a Hybrid Energy Storage System. In recent years the use of Hybrid ESS became an important issue in the literature about electric vehicles [85, 86] and also related to grid connected applications for the management of renewable energies [87, 88].

As a Hybrid solution the parallel connection between Ultracaps and Batteries is proposed. Both technologies will be connected to the same DC bus. This DC bus is then connected to the grid by an inverter with STATCOM topology. In this way the Hybrid ESS is able to supply constant 5.2MW by the batteries and a peak of 4MW by the Ultracaps and the STATCOM will be able to supply 5MVAr when the Ultracaps are not used.

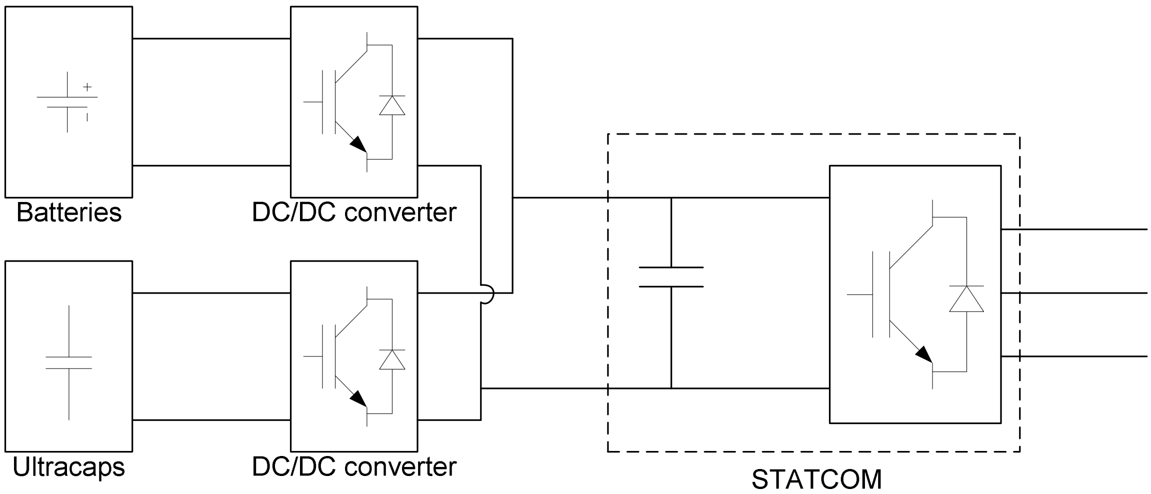

Figure 77: General topology of the proposed Hybrid ESS

7.3. Power Conversion System: DC/DC boost converter design constraints

The parallel connection of Ultracaps and Battery ESS cascaded with a STATCOM is proposed as a Hybrid solution to accomplish all the functionalities analyzed in chapter 5. The use of STATCOM with ESS is widely discussed in the literature [89-93]. At this point the parallel connection of Batteries and Ultracaps to the same DC bus by means of DC/DC boost converters will be discussed. The high current requirement of the Ultracaps to supply 4MW is the most important problem for the design of the Power Conversion System. This problem can be reduced using interleaved boost converters.

The "Interleaved" boost DC/DC converter is the parallel connection of N independent DC boost modules using an interleaved modulation. The input current is distributed uniformly through all the modules and the current ripple is minimized due to this interleaved modulation.

A design guideline for interleaved boost converters is given at this chapter. Sizing criteria for the different components of the power conversion system are given, for a converter without coupled inductors.

7.3.1. Sizing of the converter

Considering the N modules DC/DC converter of Figure 78, for current ripple analysis each module will be analyzed independently, as it is shown in Figure 79.

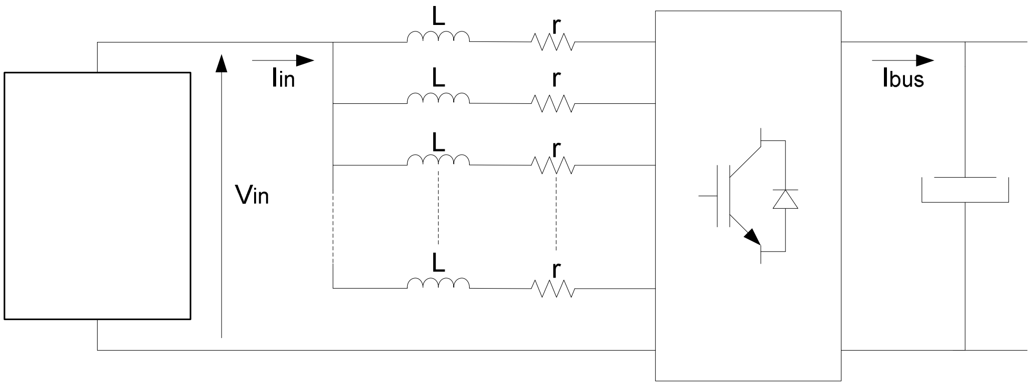

Figure 78: N modules DC/DC converter

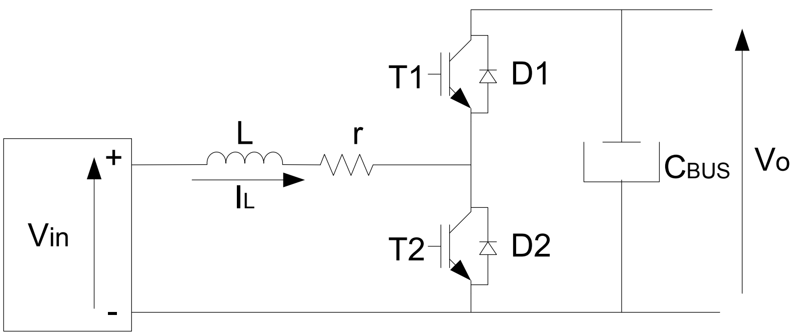

Figure 79: Equivalent circuit of each module

Each module is a bi-directional DC/DC boost converter. The relation between the input and output voltage of the converter is defined by:

$$V_o = \frac{V_{in}}{(1-\delta_{T2})} = \frac{V_{in}}{\delta_{T1}} \tag{7. 1}$$

From this equation is defined that $V_o \geq V_{in}$ for any duty cycle. Thus for an application with a variable input voltage, the output voltage should be chosen to keep $V_o \geq V_{in_{MAX}}$ in any case.

The average current through one module is:

$$\hat{I}_L = \frac{I_{in}}{N} \tag{7. 2}$$

Current ripple in the module

During the switching on of transistor T2, the derivate of the current through the inductor is:

$$\frac{di_L}{dt} = \frac{1}{L} \cdot \left(V_{in} - i_L \cdot r\right) \tag{7. 3}$$

Considering negligible the voltage drop through the resistor of the wire, the current variation is:

$$\frac{\Delta I_L^{\ +}}{T_{ON_{T2}}} \approx \frac{1}{L} \cdot V_{in} \tag{7. 4}$$

During the switching off of transistor T2, the derivate of the current is:

$$\frac{di_L}{dt} = \frac{1}{L} \cdot \left(V_{in} - V_o - i_L \cdot r\right) \tag{7. 5}$$

Considering negligible the voltage drop through the wire resistance, assuming a continuous conduction, the current variation is:

$$\frac{\Delta I_L^{\ -}}{T_{OFF_{T2}}} \approx \frac{1}{L} \cdot \left(V_{in} - V_o\right) \tag{7. 6}$$

In steady state, the positive variation of the current during T_{ON} should be equal to the negative variation of the current during T_{OFF}. Therefore can be demonstrated that the current ripple of a module in steady state is:

$$\Delta I_L = \frac{V_{in}}{L} \cdot \left(1 - \frac{V_{in}}{V_o}\right) \cdot T_{sw} \tag{7. 7}$$

Being T_{sw} the commutation period $T_{sw} = \frac{1}{f_{sw}}$

Supposing a variable input voltage, the maximum current ripple in a module corresponds to the minimum input voltage:

$$\Delta I_{L_{MAX}} = \frac{V_{in_{MIN}}}{L} \cdot \left(1 - \frac{V_{in_{MIN}}}{V_o}\right) \cdot T_{sw} \tag{7. 8}$$

This current ripple through each module is independent to the number of modules connected to the converter. This ripple appears with a converter without coupled inductors and supposing continuous current conduction through the module.

This maximum ripple will define the maximum current through the module and through each module semiconductor.

Input current ripple

That the input current ripple is minimized inserting or varying the phase of each triangular signal of the PWM modulation of the modules with an angle of 2π/N can be demonstrated. In this way the apparent commutation frequency from the point of view of the input current is $N \cdot f_{sw}$ and the apparent commutation period is T_{sw}/N.

To analyze the ripple of the input current should be taken into account that this input current is the sum of all the module currents:

$$i_{in} = \sum_{j=1}^{N} i_{Lj} \tag{7. 9}$$

So,

$$\frac{di_{in}}{dt} = \sum_{j=1}^{N} \frac{di_{Lj}}{dt} \tag{7. 10}$$

The input current variation will be given by the sum of all the modules current variations. The module current variation depends on the state of commutation of transistor T2 of each module, as described in equations (7. 4) and (7. 6).

Using an interleaved modulation, varying the phase of the triangular modulation signals with a $\frac{2\pi}{N}$ angle, the switching on and off angle of each transistor of the different modules is varied $\frac{2\pi}{N}$. So the apparent commutation from the point of view of the input current will be equal to this angle $T_{SW_{APARENTE}} = \frac{T_{SW}}{N}$. With one duty cycle of transistor T2 between $0 \le \delta_{T2} \le \frac{1}{N}$ the switching on time of T2 transistors is less than the angle $\frac{2\pi}{N}$, therefore smaller than apparent commutation period. This means that during the apparent commutation period, only one of the transistors T2 can be switched on (as a result also the current of each module with positive slope). Therefore when one transistor T2 is conducting, its module will have positive slope and the rest modules have negative slope. When the transistor stops conducting the current of all the modules will have negative slope until other transistor T2 is switched on during the next apparent commutation period.

In steady state the net input current variation should be zero, this means that the input current will have a positive variation during the conduction of transistor T2 and obviously the variation will be negative when it is not conducting any transistor.

Knowing that the input current variation is the sum of all the module current variations and using equation (7. 3) and (7. 5), for $0 \le \delta_{T2} \le \frac{1}{N}$:

$$\frac{\Delta I_{in}^{+}}{T_{ON_{T2}}} = \frac{1}{L}\left[\left(V_{in} - i_L \cdot r\right) + (N-1)\cdot\left(V_{in} - V_o - i_L \cdot r\right)\right] \qquad (7.\ 11)$$

Developing this:

$$\frac{\Delta I_{in}^{+}}{T_{ON_{T2}}} = \frac{1}{L}\left[N \cdot \left(V_{in} - i_L \cdot r\right) - (N-1) \cdot V_o\right] \quad (7.\ 12)$$

In steady state, this variation will be equal to the input current ripple.

For a duty cycle between $\frac{1}{N} \leq \delta_{T2} \leq \frac{2}{N}$, the switching on time of the transistor will be larger than the apparent commutation period. This means that in every moment at least one T2 transistor will be conducting and during certain period two transistors will conduct. In every moment there will be a module with positive current slope and periods of current overlap of two transistors, where two modules will have positive current slope. In steady state the net input current variation will be zero, hence it should have a positive current slope during overlap conduction of two transistors T2 and negative slope only when one transistor is conducting. The overlap period is equal to the switching on period of a transistor T2 minus one apparent commutation period:

$$T_{OVERLAP} = \left(\delta_{T2} - \frac{1}{N}\right) \cdot T_{sw} \quad (7.\ 13)$$

Hence as in equations (7. 11) and (7. 12), for one duty cycle between $\frac{1}{N} \leq \delta_{T2} \leq \frac{2}{N}$, the positive current variation is:

$$\frac{\Delta I_{in}^{+}}{T_{OVERLAP}} = \frac{1}{L}\left[2 \cdot \left(V_{in} - i_L \cdot r\right) + (N-2) \cdot \left(V_{in} - V_o - i_L \cdot r\right)\right] \quad (7.\ 14)$$

Developing this equation:

$$\frac{\Delta I_{in}^{+}}{T_{OVERLAP}} = \frac{1}{L}\left[N \cdot \left(V_{in} - i_L \cdot r\right) - (N-2) \cdot V_o\right] \quad (7.\ 15)$$

For a duty cycle between $\frac{2}{N} \leq \delta_{T2} \leq \frac{3}{N}$ the switching on period of transistors T2 will be more than two apparent commutation periods, thence there will be always two transistors

T2 conducting and there will be an overlap period of three transistors conducting simultaneously. This overlap period is:

$$T_{OVERLAP} = \left(\delta_{T2} - \frac{2}{N} \right) \cdot T_{sw} \tag{7. 16}$$

Like in previous cases the current variation is defined by:

$$\frac{\Delta I_{in}^{\ +}}{T_{OVERLAP}} = \frac{1}{L} \left[N \cdot \left(V_{in} - i_L \cdot r \right) - (N-3) \cdot V_o \right] \tag{7. 17}$$

Generalizing these equations for any interleaved converter of any number of modules, for a duty cycle between $\frac{(k-1)}{N} \leq \delta_{T2} \leq \frac{k}{N}$, being k=1, 2, 3… N, there will be always at least $(k-1)$ transistors T2 conducting and there is an overlap period of k transistors T2 conducting. This overlap period is:

$$T_{OVERLAP} = \left(\delta_{T2} - \frac{k-1}{N} \right) \cdot T_{sw} \tag{7. 18}$$

Therefore in the same way as it has been calculated for previous cases the input current ripple is:

$$\Delta I_{in}^{\ +} = \left(\delta_{T2} - \frac{k-1}{N} \right) \frac{T_{sw}}{L} \left[N \cdot \left(V_{in} - i_L \cdot r \right) - (N-k) \cdot V_o \right] \tag{7. 19}$$

Being *k*=1, 2, 3,… N

Equation (7. 1) relates input and output voltage depending on the duty cycle. For a constant output voltage and a variable input voltage, equation (7. 19) can be defined as:

$$\Delta I_{in}^{\ +} = \left(\delta_{T2} - \frac{k-1}{N} \right) \frac{T_{sw}}{L} \left[N \cdot \left(V_o \cdot \left(1 - \delta_{T2} \right) - i_L \cdot r \right) - (N-k) \cdot V_o \right] \tag{7. 20}$$

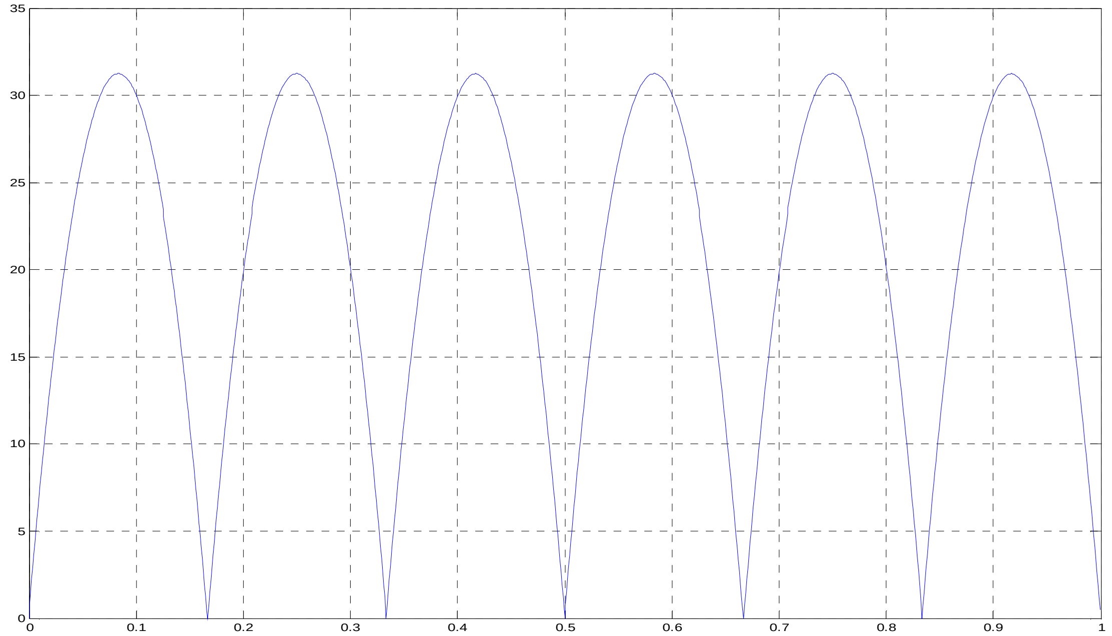

Figure 80: Current ripple in function of the duty cycle, for constant output voltage

Figure 80 shows the evolution of the ripple in function of the duty cycle, for a 6 modules converter. As duty cycle varies, there are several ripple lobes, of which number is equal to the number of modules of the converter. The maximum ripple is the same for all the lobes. These maximums are when:

$$\frac{\partial \Delta I_{in}}{\partial \delta_{T2}} = 0$$

With the pertinent calculations, the maximums are in:

$$\delta_{T2_{MAX}} = \frac{1 - \frac{i_L \cdot r}{V_o} - \frac{N-k}{N} + \frac{k-1}{N}}{2} \quad \text{For k=1, 2, 3... N} \tag{7. 21}$$

The maximum value of current ripple is:

$$\Delta I_{in_{MAX}} = \frac{N \cdot (V_o - i_L \cdot r) - V_o \cdot (N-1)}{2N \cdot V_o} \cdot \frac{T_{sw}}{L} \cdot \left(\frac{V_o}{2} - \frac{N}{2} \cdot i_L \cdot r \right) \tag{7. 22}$$

Considering that $V_o \rangle\rangle i_L \cdot r$:

$$\Delta I_{in_{MAX}} \approx \frac{1}{2N}\cdot\frac{T_{sw}}{L}\cdot\frac{V_o}{2} \qquad (7.\ 23)$$

In case of the input voltage is constant and the output voltage is variable, equation (7. 18) can be rewritten substituting equation (7. 1):

$$\Delta I_{in}^{\ +} = \left(\delta_{T2} - \frac{k-1}{N}\right)\frac{T_{sw}}{L}\left[N\cdot\left(V_{in} - i_L\cdot r\right) - (N-k)\cdot\frac{V_{in}}{1-\delta_{T2}}\right] \qquad (7.\ 24)$$

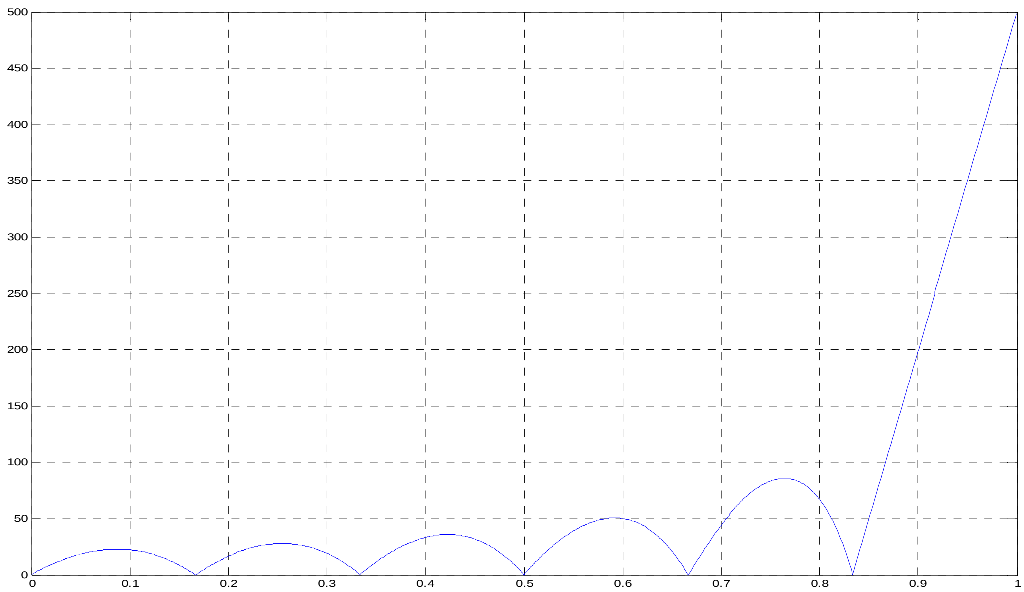

Figure 81: Current ripple in function of the duty cycle, for constant input voltage

Figure 81 shows the input current ripple depending on the duty cycle for a 6 modules converter. There appear again as much lobes as number of modules, but the maximum value of each lobe is variable. Calculating again the duty cycles when these maximums are given by $\frac{\partial \Delta I_{in}}{\partial \delta_{T2}} = 0$, the ripple maximums are in:

$$\delta_{T2_{MAX}} = 1 - \sqrt{\frac{-(N-k)\cdot V_{in}\cdot\left(\frac{k-1}{N} - 1\right)}{N\cdot\left(V_{in} - i_L\cdot r\right)}} \qquad (7.\ 25)$$

Being k=1,2,3… N

Substituting this value in equation (7. 23) the maximum ripples for each duty cycle level can be calculated.

7.3.2. Sizing of DC Bus capacitor

Voltage ripple due to interleaved converter

The voltage ripple will be calculated considering only the voltage ripple due to the output current of the interleaved converter, considering the general case of N levels shown in Figure 78 and Figure 79. Supposing a duty cycle for the transistors between $\frac{(k-1)}{N} \leq \delta_{T2} \leq \frac{k}{N}$, being *k*=1, 2, 3… N, it was deduced previously that there will be always at least $(k-1)$ transistors T2 conducting, being an overlap period calculated in equation (7. 18) in which there will be *k* transistors T2 conducting simultaneously.

From the point of view of the output current of the interleaving converter towards the DC bus, in Figure 79 can be appreciated clearly that when transistor T2 is conducting in one module, the current of this module is not going towards the DC bus. However while transistor T2 is opened the module current will circulate towards the DC bus. Therefore during the overlap period of the output current from the converter to the DC bus, I_{BUS}, will be the sum of the current of $(N-k)$ modules. Out of this overlap period the current I_{BUS} will be the sum of currents of $(N-k+1)$ modules.

In order to make calculations easier the effect module current ripple will be neglected and it will be supposed an equilibrated share of current between all the modules. Therefore the module current will be considered constant and equal to the average module current calculated in (7. 2). Assuming these approximations, the output current of the converter I_{BUS} will be rectangular between $(N-k)\cdot\frac{I_{in}}{N}$ and $(N-k+1)\cdot\frac{I_{in}}{N}$.

The average value of the current through the bus capacitor in steady state will be zero. Therefore the voltage ripple will be caused by rectangular shape of the interleaved converter output current, making the previously mentioned simplifications, so supposing that the rest of elements connected to the DC bus do not affect to the voltage ripple. It can be demonstrated that the worst case for the voltage ripple will be with a 50% cycle for the rectangular I_{BUS} current. In this case the current through the capacitor will be $+\frac{I_{in}}{2N}$ during $\frac{T_{sw}}{2N}$ (half of the apparent commutation period) and $-\frac{I_{in}}{2N}$ during other $\frac{T_{sw}}{2N}$ seconds.

Therefore the maximum DC bus voltage ripple due to the interleaved converter output current is approximately equal to:

$$\Delta V_{BUS_{MAX}} \approx \frac{1}{C_{BUS}} \cdot \frac{I_{in} \cdot T_{sw}}{4 \cdot N^2} \tag{7. 26}$$

Bus capacitor sizing criterion

To calculate the size of the DC bus capacitor, the criterion to limit the maximum voltage ripple at the bus results an adequate criterion for many applications where a DC/DC interleaved converter is used. In order to define this criterion should be taken into account not only the ripple due to the interleaved converter and calculated by equation (7. 26), but also should be taken into account the voltage ripple caused by other converters or elements that could be connected to the same DC bus. If it is known that the effect of the other devices connected to the same bus is negligible compared to the ripple caused by the interleaved converter, from equation (7. 26) could be deduced the value of the capacitor required to maintain the voltage ripple under certain limits:

$$C_{BUS} \geq \frac{1}{\Delta V_{BUS_{LIM}}} \cdot \frac{I_{in} \cdot T_{sw}}{4 \cdot N^2} \tag{7. 27}$$

Nevertheless if the ripple caused by other elements connected to the same DC bus would not be negligible, the ripple caused by these elements should be calculated and assume that in the worst case the voltage ripple can be the sum of all the ripples caused by all the elements connected to the DC bus. Obviously this is not true when there is any synchronism or coordination between the different elements in order to minimize this ripple.

Other important factor, especially in high power applications, is the dynamic of the converter or the device used to control the DC bus voltage. If the dynamic of the dispositive is slow and is not able to act in the face of variations on the power supplied to the bus (what is common in high power applications), the bus capacitor should be able to absorb these power variations with the consistent DC bus voltage variation. In low power applications, where the dynamics of different elements are large and power relatively low, these variations are not important and the bus capacitor can be sized taking into account only the maximum ripple criteria, previously mentioned.

Other factor to take into account to size the DC bus is the security of the system. Considering a case in which maximum current is circulating through the inductances and converters are disconnected, the increase of bus voltage should be under the 10% of the nominal.

For the converter of Figure 78, can be demonstrated that the total energy stored in all the module inductors, considering an equilibrated input current share, is:

$$E_L = \frac{1}{2N} \cdot L \cdot I_{in}^{\ 2} = \frac{1}{2} C_{BUS} \left((1.1 \cdot V_{BUS})^2 - V_{BUS}^{\ 2} \right) \qquad (7.\ 28)$$

For a stored energy at the bus approximately equal to the energy stored at the module inductors, the following relation fulfilled:

$$C_{BUS} \approx \frac{1}{0.21 \cdot N} \cdot L \cdot \left(\frac{I_{in}}{V_{BUS}} \right)^2 \qquad (7.\ 29)$$

Nevertheless, this expression would be a first approach of the capacitor value, which could be valid in many applications but could not be sufficient in many others.

7.4. Practical system design

The storage system is directly connected to the 690V low voltage power grid through a three-phase two-level inverter. For this application a 1200V DC bus is required. This voltage is the output DC bus voltage of the DC/DC interleaved converter, and is going to be constant at all conditions. The nominal power of the storage system is set to 4MW, and the Ultracaps have to be able to develop this nominal power during at least 2 seconds during power surge requirements, until the batteries are able to response to the grid power demand.

As shown in (7. 1) the Ultracaps voltage should be lower than 1200V. It is decided to use the BMOD0063 Ultracaps module from Maxwell Technologies, 8 of these Ultracaps modules of 125V connected in series with 6 lines in parallel, being a total of 48 modules.

The total capacitance of the Ultracaps group is C=47.25 F and the total ESR=24 mΩ.

At the capacitor nominal voltage of 1000V, for obtaining the nominal output power of 4MW it is needed an output current of 4059.3 A, being the output voltage of the Ultracaps group of 985.39V. At the capacitor minimum voltage of 623.715 V for obtaining the nominal output power of 4 MW it is needed an output current of 6413.2 A.

These output voltages and output currents of the Ultracaps group are the input voltage and currents of the bidirectional interleaved DC/DC converter.

Using (7. 8), an adequate branch inductance value could be calculated for an acceptable branch current ripple. This branch current ripple does not depend on the number of interleaved modules used in the converter. So the inductance value could be calculated before deciding the number of modules to use in the converter. Analyzing the power and current requirements of the converter, it is decided to use a switching frequency of 1kHz for the converter.

Taking as criterion a maximum branch-current ripple of 10% of the maximum total input current:

$$L \geq \frac{V_{in_{MIN}}}{\Delta I_{L_{MAX}}} \cdot \left(1 - \frac{V_{in_{MIN}}}{V_{o_{MAX}}}\right) \cdot T_{sw} \tag{7. 30}$$

$$L \geq 0.467 mH \tag{7. 31}$$

Inductancies of L=1mH will be used.

Equation (7. 23) describes the maximum input current ripple of the interleaved converter, with a constant output voltage and a variable input voltage. In Ultracaps applications it is very important to minimize the output current ripple of these Ultracaps modules. Therefore, in this application it is decided to use 6 interleaved modules in parallel, so the maximum Ultracaps current ripple (at some duty cycles) would be:

$$\Delta I_{in_{MAX}} \approx 50A \tag{7. 32}$$

With N=6, the average value of the branch current would be:

$$\hat{I}_L = \frac{I_{in}}{N} \approx 1068.87A \tag{7. 33}$$

As a sizing criterion of filter inductances a 10% of Ultracaps output current ripple is taken. In this case the maximum ripple is given for the minimum value of V_{in} and for a commutation frequency of 1kHz, using equation (7. 8):

$$\Delta I_{L_{MAX}} = 300A \tag{7. 34}$$

So the peak current that would circulate through the converter in the worst case would be equal to 1218.87A. Figure 82 shows the six steady state branch currents for this worst case.

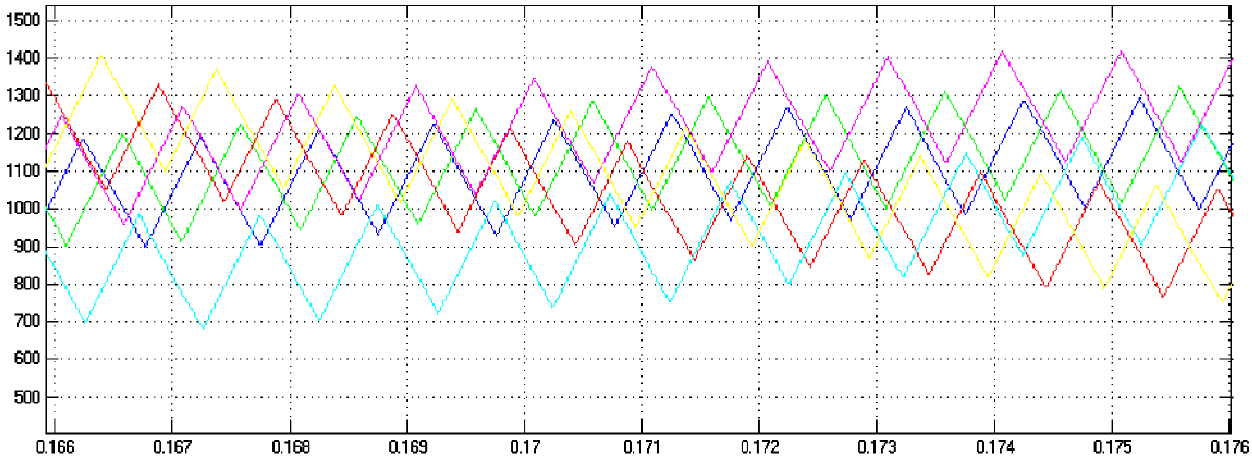

Figure 82: Current ripple through the 6 brands of the converter.

The DC bus capacitor sizing criterion is based on (7. 29). Substituting the previously calculated values:

$$C_{BUS} \approx 22.6mF \tag{7. 35}$$

A C_{BUS}=25mF is then chosen.

Figure 83 shows the DC bus voltage with Ultracaps output current variation, from 0 to full power of 4MW.

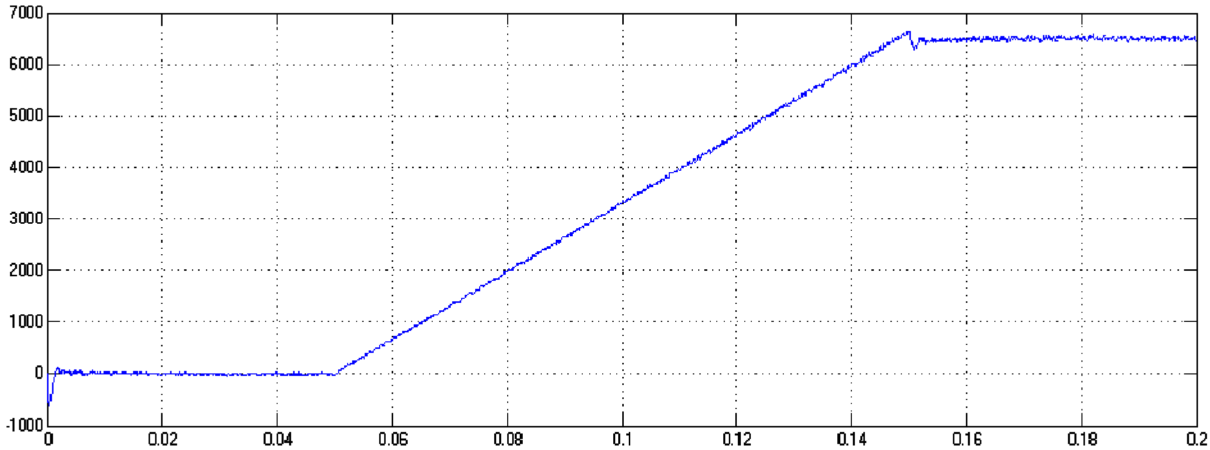

Figure 83: DC bus voltage (V_o) variation with Ultracaps current (I_{in}) variation

7.5. Chapter conclusions

In this chapter an integral ESS solution has been proposed in order to have a single solution for the different applications of ESS for Grid Support that have been analyzed in chapter 5. A Hybrid ESS is a solution that may respond to fast transient deviations of voltage and frequency, but also to continuous grid support applications like Primary Frequency Regulation.

From the sizing criteria proposed in the previous chapters is defined the size of the proposed Hybrid ESS. Finally a connection topology for the proposed Hybrid ESS has been proposed. The interleaved boost converters are proposed as a suitable solution for the parallel connection of Batteries and Ultracaps.

The implementation of a Hybrid ESS that combines different storage technologies may be an integral solution for the Grid Support of weak power systems. The proposed system combines the fast dynamic of a STATCOM for reactive power compensation, the ability of Ultracaps to supply a large power peak very fast and the power reserve of Li-ion batteries. With these properties the proposed system may control the voltage, respond to the tripping of a generator avoiding the load shedding and contribute to the Primary Frequency Regulation.

Chapter 8

Conclusions

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8. Conclusions

8.1. Conclusions

With the present thesis the use of Energy Storage Systems in the face of the massive implementation of renewable energies and Distributed Generation is analyzed. In this work, we have investigated and discussed the impact of DG on power systems paying attention on weak power systems, like islands or rural networks.

The overview about different ESS technologies shows the diversity of technological solutions available. Nowadays Ultracaps and new technologies of Batteries (Li-ion, NaS, Flow batteries…) are the most developed technologies for grid connected applications.

Power system studies are usually based on computer simulations. This simulation-based approach is used in this work as well. For this purpose, we have introduced the dynamic calculation of power flows as a solution to simulate the voltage and frequency behavior of a power system. To study the contribution of ESS in electrical grids different components of power systems are modeled. The implementation of these models in the proposed simulation tool permits to analyze the different scenarios proposed in this work.

Grid operation, focused on voltage and frequency stability, has been analyzed. The analysis of these problems has been the base to analyze the contribution of ESS in weak power systems with high penetration of DG.

The contribution of ESS in weak power systems with high penetration of DG has been discussed and confirmed by simulations. In the face of bi-directional power flows the implementation of active control technologies at substations has been proposed in order to ensure the stability of voltage, especially in remote areas with high penetration of DG.

The tripping of a generation unit in a small power system has been analyzed. The injection of a large peak of power is necessary to avoid the load shedding in a power system in these conditions. The use of Ultracaps has been proposed as a solution.

The use of ESS for primary frequency regulation has been analyzed. Since frequency regulation is an almost zero energy cost application the use of batteries has been proposed in order to reduce the use of generators for primary power reserve.

The variability of wind energy and other renewable energy sources is an important problem for an electrical grid that aims to supply the 20% of the electricity demand from these resources. The use of ESS in combination with wind farms has been proposed as a solution to this problem. A management strategy has been proposed in order to forecast the dispatch of a wind farm in ten minutes periods.

A Hybrid ESS that combines Batteries and Ultracaps has been proposed as an integral solution that combines the different applications of ESS that have been analyzed in the present work. This kind of Hybrid ESS might be commercialized as an adaptable solution to many different scenarios.

The ESS technologies field is an industry that is growing very fast. The development in recent years of new ESS technologies is pushing on the use of these technologies for grid connected applications. The evolution of the costs of these technologies will be a key issue in order to favor the installation of these technologies for grid connected applications. With the actual costs it seems necessary to subsidize the installation of ESS since it will be necessary the use of these technologies in the electrical grid of the future, with high penetration of renewable energies. A study about the investment and amortization of ESS is carried out in the Annexe B.

8.2. Publications

Several publications have been presented in different conferences in order to present the work that has been presented in this document.

- "Design of control strategies to improve grid integration in fixed speed wind energy systems with battery storage" A. Goikoetxea, M. Rodriguez, H. Bindner y A. Milo, en el congreso ICREPQ ‘08 Santander, 2008.
- "Benefits of distributed energy storage working in parallel to distributed energy resources" A. Goikoetxea, J. A. Barrena, M. A. Rodriguez y G. Abad, en el congreso ICREPQ ‘09 Valencia 2009.
- "Active Substation Design to Maximize DG Integration" A.Goikoetxea, J. A. Barrena, M. A. Rodriguez, and G. Abad, en el congreso PowerTech ‘09 Bucharest (Rumanía), 2009.
- "Grid manager design using Battery Energy Storage Systems in weak power systems with high penetration of wind energy" A. Goikoetxea, J. A. Barrena, M. A. Rodriguez y G. Abad, en el congreso ICREPQ ‘10 Granada, 2010.
- "Frequency restoration in insular grids using Ultracaps ESS" A. Goikoetxea, J. A. Barrena, M. A. Rodriguez y F. J. Chivite, en el congreso Power Electronics Electrical Drives Automation and Motion (SPEEDAM), 2010 International Symposium, 2010.

8.3. Future Lines

The present thesis researched about the operation of electrical grids with high penetration of DG using ESS. In the research line of Electrical Energy in Mondragon Unibertsitatea the operation of the electrical grid and the contribution of Energy Storage

System for utility applications were not investigated before this thesis. Therefore this thesis opened a new research line within the University.

Furthermore the interest of the university and Ingeteam Company on this scientific research shows the interest of the topic. Actually new research projects are going to be developed in collaboration between Mondragon Unibertsitatea and Ingeteam in this field.

From the conclusions of this thesis new research lines are proposed:

- A Hybrid ESS is proposed in this thesis and several design constraints are given. The implementation of the proposed device will be the next step. The implementation of a first prototype is planned to be done in few months.
- The implementation of Active Substations to control the voltage in substations with high penetration of DG has been proposed. A deeper analysis of this concept in order to design the proposed solution will be necessary, regarding its implementation.
- Four different applications have been analyzed in this thesis. After this first technical analysis an economic analysis will be necessary in order to implement the proposed applications. The solutions proposed based on the use of ESS should be compared by other solutions in order to compare the pros and cons of the different solutions.
- From the utility applications of ESS mentioned in the introduction only applications related to T&D and Generation were analyzed. With the actual liberalized Electricity Market it will be very interesting to analyze applications related to Customers.
- The Dynamic Power Flow simulation tool proposed in this thesis permits the analysis of electrical grids. In this way new researches related to the operation of electrical grids may be carried. In the actual context of change of electrical grids many new research lines may be opened: Smart Grids, Intelligent Load Management, management of grid connected vehicles storage capacity etc. may be analyzed using the proposed simulation tool.

Chapter 9

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9. References

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Annexes

Annexes

A. Per Unit representation

Per-unit system is the expression of system quantities as fractions of a defined base unit quantity. Calculations are simplified because quantities expressed as per-unit are the same regardless of the voltage level. Similar types of apparatus will have impedances, voltage drops and losses that are the same when expressed as a per-unit fraction of the equipment rating, even if the unit size varies widely. Conversion of per-unit quantities to volts, ohms, or amperes requires knowledge of the base that the per-unit quantities were referenced to.

A per-unit system provides units for power, voltage, current, impedance, and admittance. Only two of these are independent, usually power and voltage. All quantities are specified as multiples of selected base values. For example, the base power might be the rated power of a transformer, or perhaps an arbitrarily selected power which makes power quantities in the system more convenient. The base voltage might be the nominal voltage of a bus. Different types of quantities are labelled with the same symbol (pu).

Generally base values of power and voltage are chosen. Once the base power and the base voltage are chosen, the base current and the base impedance are determined by the natural laws of electrical circuits. The relationship between units in a per-unit system depends on whether the system is single phase or three phase.

Single phase

Assuming that the independent base values are power and voltage:

$P_{base} = 1pu = S_{base} = Q_{base}$

$V_{base} = 1pu$

The rest of the units can be derived from power and voltage using the equations

$S = I \cdot V$

$P = S \cdot \cos(\phi)$

$Q = S \cdot \sin(\phi)$

$$\vec{V} = \vec{I} \cdot \vec{Z}$$

Z being represented by

$$\vec{Z} = R + jX = Z\cos(\phi) + jZ\sin(\phi)$$

$$I_{base} = \frac{S_{base}}{V_{base}} = 1pu$$

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^{\;2}}{S_{base}} = 1pu$$

$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

Three phase power and voltage are specified in the same way as single phase systems. However, due to differences in what these terms usually represent in three phase systems, the relationships for the derived units are different. Specifically, power is given as total (not per-phase) power, and voltage is line to line voltage. In three phase systems the equations P = S·cos(ϕ) and Q = S·sin(ϕ) also hold.

$$S_{base} = \sqrt{3} \cdot V_{base} \cdot I_{base}$$

$$I_{base} = \frac{S_{base}}{V_{base} \cdot \sqrt{3}} = 1pu$$

$$Z_{base} = \frac{V_{base}}{I_{base} \cdot \sqrt{3}} = \frac{V_{base}^2}{S_{base}} = 1pu$$

$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

B. Benefits of distributed energy storage working in parallel to distributed energy resources

B.1. Introduction

The electrical grid is one of the largest infrastructures ever built. This infrastructure has been built regarding a generation model where large centrals should provide the electricity to supply all the customers. In this grid topology, the power produced by these centrals is transmitted in HV to consumption points, changing there to MV for its distribution and finally is transformed to LV for its consumption. Due to environmental concerns and the variable price of fossil fuels, renewable energy sources are getting more importance for power generation. Even if large wind farms or hydroelectric centrals are connected to the transmission grid, a large amount of renewable energy is connected to the distribution network. These generation units can be defined as distributed generation (DG). The increasing penetration of DG is already changing the network topology [1]. Due to the policies that aim the increase of renewable energies, subsidizing the electricity produced by renewable sources and the liberalization of electricity markets are promoting this change of the network topology.

In this context many customers are becoming electricity suppliers. Distribution grid operators are forced to buy this electricity but the price of this electricity can be variable depending on the power quality and time-slot. In Spain the R.D.661/2007 gives the chance to DG owners to sell the electrical power in the free market complemented by a bonus or in a fixed price. This rule defines also the complements for the control of reactive power, depending on the power factor or the needs of distribution system operators. Using energy storage with a STATCOM connected in parallel to DG units it is an interesting technology in order to get as much benefits as possible, on the one hand it gives the possibility to store the electricity when the price is low to sell it when the price is high, on the other hand the STATCOM gives the possibility for reactive power compensation.

Furthermore, the use of power converters gives different possibilities, such as active and reactive power compensation of loads, network voltage control and mitigation of power system disturbances [2]. The use of batteries for the active management of distribution grids is discussed in [3], showing the possibility of developing a storage system suitable for improving the quality of supply on a grid and how a droop control of voltage and frequency enables the island operation.

At this point the possible benefits of a Statcom with energy storage systems working in parallel to DG are analyzed, from the point of view of DG owners. In this way, there will be discussed the most convenient management strategies in order to obtain economical profits for the DG owner. Therefore, the management strategy to sell as much power as possible when the price of the electricity is high in the market is going to be developed, controlling the reactive power to get as high complement as possible.

B.2. Spanish electricity market

Spain has a liberalized electricity market and is within the Iberian market. The price of the electricity depends on the offer of qualified suppliers and the demand of the qualified customers. There is an intermediate company (OMEL) for the economical management of the electricity market that assures the correct balance of the offer demand and the free competition. The electricity production market is divided in 4 processes, the diary market process where a first price is fixed depending on the offer and demand of each day, the solution of technical restrictions process, interdiary market process and the ancillary services and deviation management process. In this way a first price for the next day kWh is fixed for every, although the final price is fixed monthly after analyzing these four processes. For the wind farms there are two choices to sell electricity: sell it in a fixed price or sell it the free market complemented by a bonus. The bonus for the free market establishes a minimum and maximum price for the kWh of wind energy[94].

B.3. Battery storage technologies

Traditionally lead acid batteries have been used for electricity storage. The low cost and the maturity of this technology makes it still an interesting option for electricity storage.

Even so the waste of these batteries is very toxic and this made interesting the development of other technologies. The REDOX flow batteries and the NaS batteries are the most mature technologies; many installations of these technologies there have been implemented during the last years. The storage cost is higher than lead acid batteries, but for discharge times of three hours the cost is the similar for REDOX and is not so high for NaS, but the cycle life is longer with these technologies, compared to lead acid batteries [95].

B.4. Scenario for the study

In order to analyze the economical benefits provided by a STATCOM with energy storage for the owners of DG installations it has been chosen the scenario developed in [66].

The scenario proposed is composed by a wind farm connected to the MV distribution network, working in parallel to a battery connected to the PCC by a Statcom..

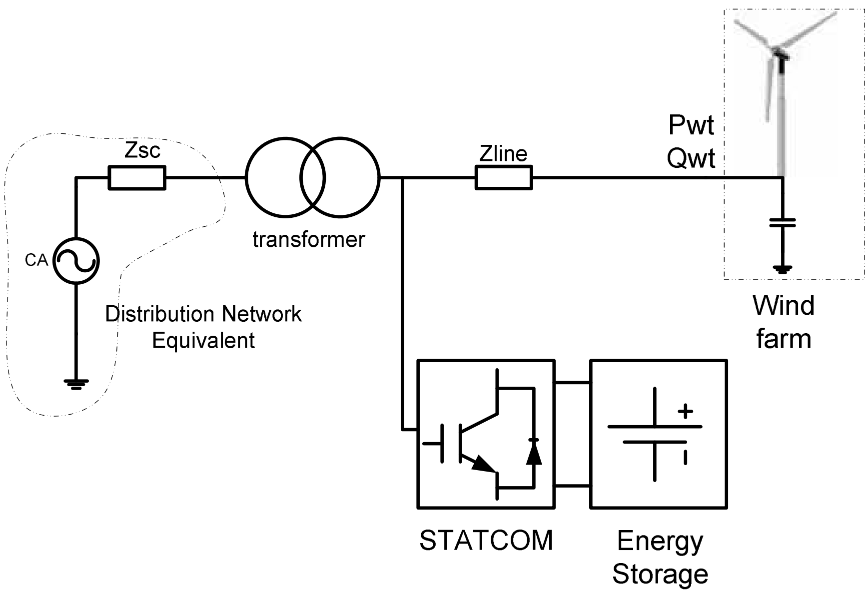

Figure (Annexes) 1: Scenario proposed for the study

B.5. System modeling

B.5.1. Distribution grid

The distribution network equivalent grid will be modeled in a first stage as an ideal voltage source with a short-circuit impedance with an adequate X/R ratio. In this case the short circuit impedance is defined around the 10% of the nominal power of the wind farm, in order to simulate a weak network.

The X/R ratio in distribution grids is around 10.

B.5.2. Wind turbine

The fixed speed turbine model is composed of five cascaded elements:

- Wind profile, aerodynamic system and mechanical system.
- Asynchronous generator.

B.5.3. Statcom

The Statcom is composed of a three phases voltage source inverter connected to the grid by means of an inductive filter. In order to reduce the simulating time the modulator and the switches will be modeled as voltage controlled sources.

B.5.4. Storage system

The storage system is composed by the battery and the DC/DC converter. The converter is modeled by its medium model and the battery by means of an electrical model taking into account the battery lifetime and the voltage-current characteristics.

B.6. Control strategies

The control strategies are divided in two levels of control hierarchy:

B.6.1. Converter control

The converter control is responsible for active and reactive power exchange by the grid inverter control and the current control of battery. Among all the control strategies proposed for the voltage source inverter, for this study a vector control has been selected. In this case, it will receive as references, the active and reactive power supplied by the inverter. The bus voltage will be controlled by means of the control of the battery current, so a bus voltage regulator will provide a battery current reference. The crowbar control will act as a security system.

B.6.2. Grid control

The grid control consists of defining the active and reactive power references for the inverter. Depending on the price of the electrical energy and the prediction of wind power generation it will be interesting to absorb or supply power from the battery regarding to maintain the state of charge of the battery within safety limits, the active power reference for the battery will be defined taking into account the following variables. The price of wind power in the free market varies drastically depending on the time slot and it is directly related to the power consumption [96]. The control algorithm consists of storing energy during valley and plain time slots to supply the full power during peak time slot when the price should be normally the highest, as an exception during other time slots if the price of the electricity in the market is so high the battery would supply full power as well. The reactive power reference will be defined in order to control the power factor in the PCC, to get as much bonus as possible. In Spain the appendix V of R.D.661/2007 defines the reactive power bonus complement for DG owners.

Power Factor type	Power Factor	Bonus %		
		Peak	Plain	Valley
Inductive	PF<0,95	-4	-4	8
	0,96>PF>0,95	-3	0	6
	0,97>PF>0,96	-2	0	4
	0,98>PF>0,97	-1	0	2
	1,00>PF>0,98	0	2	0
	1,00	0	4	0
Capacitive	1,00>PF>0,98	0	2	0
	0,98>PF>0,97	2	0	-1
	0,97>PF>0,96	4	0	-2
	0,96>PF>0,95	6	0	-3
	PF<0,95	8	-4	-4

Table (Annexes) 1: bonus complement for reactive power, defined in R.D.661/2007

B.7. Simulations

The aim of the simulations is to show the benefits of an energy storage system for DG owners, following the previously mentioned control strategy. In this way, there will be calculated the economical profit of using a battery in parallel to a wind farm. Different simulations were made in order to analyze different opportunities for a 5MW wind farm; these results can be extrapolated to larger installations.

In a first step there were calculated the benefits of a wind farm selling the electricity in the free market with bonus and selling it to a fixed price. Afterwards there has been simulated the scenario of a Battery Energy Storage System (BESS) working in parallel to a wind farm. This system was analyzed for different storage capacities and different power conversion systems. Using the approximated costs of different BESS technologies [97] and the yearly benefits of the use of each battery in parallel to a wind farm, there is calculated the amortization time of the investment. The yearly benefits are considered the difference between the systems with the battery and the benefits of the wind farm itself without electricity storage. In these benefits are considered the sale of electricity and the bonus for reactive power control.

B.7.1. Simulation data

For the simulations was chosen the wind speed data, measured in a wind farm located on Oiz Mountain, Bizkaia, this data is available in [78]. Ten minutes mean wind speed it has been used.

The hourly price of the electricity in Spain is given in [94]. The sale of wind energy in Spain is complemented by a bonus that establishes a minimum and maximum price, this price is settled in 7,1275c€/kW as minimum and 8,4944c€/kW as maximum. With these data it has been simulated the previously defined system.

For the estimation of the investment on the BESS there have been chosen the following approximated costs from [95, 97] including the the battery and the power conversion system: for lead-acid batteries 260€/kWh and 325€/kW, for NaS batteries 270€/kWh and 350€/kW, for flow batteries 220€/kWh and 330€/kW. The investment for an on-shore wind farm is normally between 1000 and 1500€ per kW.

B.7.2. Simulation results

A Backward-Forward sweep Power Flow algorithm developed in [98] was used as a function to simulate the system in Matlab/Simulink.

Furthermore it has been calculated the amortization time if the wind power would not get any bonus, for the best case of the table. The results were improved notably and the amortization time was reduced to 50 years.

In the following figures there are different graphs of the simulations, where there are shown the wind speed, the power balance between the win farm and the battery, the energy stored in the battery and the price of the electricity during a certain period of time. These simulations were done for an 8MWxh battery with a nominal power of 2MW. In the graph of electricity price there are the price of electricity in the free market and the price wind power electricity.

			Lead acid		NaS		Flow batteries	
Power (MW)	Energy (MWxh)	Profits (€/year)	Investment (€)	Amort. (years)	Investment (€)	Amort. (years)	Investment (€)	Amort. (years)
5	40	52858,79	11931685,25	226	12672541,52	240	10391484,05	197
10	40	83959,89	13569367,54	162	14427201,12	172	12048662,55	144
4	32	43870,39	9545348,20	218	10138033,22	231	8313187,24	189
8	32	50430,70	10855494,03	215	11541760,89	229	9638930,04	191
3	24	34112,72	7159011,15	210	7603524,91	223	6234890,43	183
6	24	45498,45	8141620,52	179	8656320,67	190	7229197,53	159
2	16	19816,38	4772674,10	241	5069016,61	256	4156593,62	210
4	16	37981,47	5427747,01	143	5770880,45	152	4819465,02	127
1	8	11352,58	2386337,05	210	2534508,30	223	2078296,81	183
2	8	20004,82	2713873,51	136	2885440,22	144	2409732,51	120

Table (Annexes) 2: Results of simulations

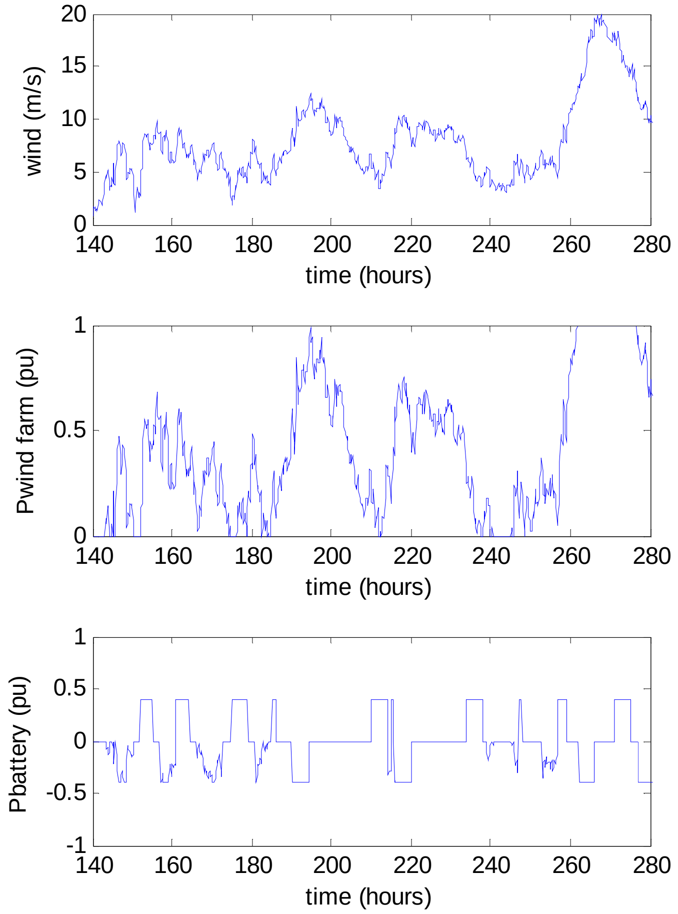

Figure (Annexes) 2: Temporal simulation

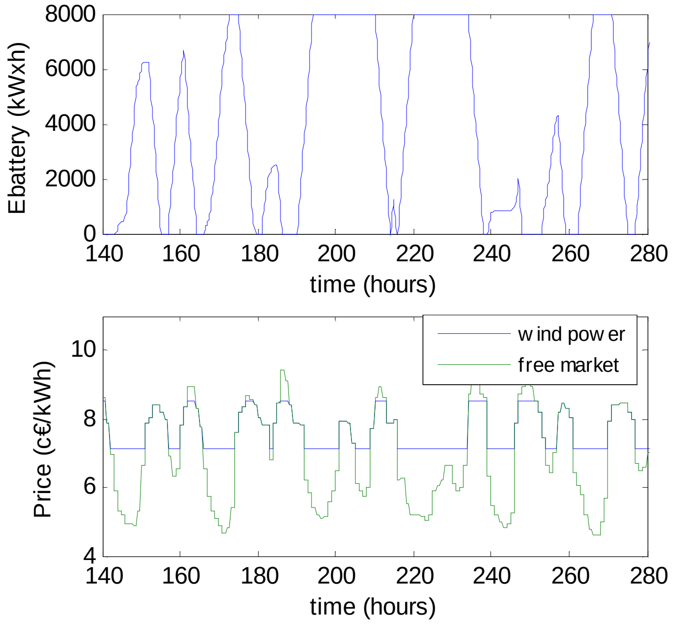

Figure (Annexes) 3: Temporal simulations

B.8. Conclusions

Regarding the aim of Spain and EU to increase the penetration of wind power to a 20% of the total electricity production in 2020 and due to the variability of wind power production, the problematic of the grid stability will come up as one of the main problems for the further increase of renewable energy production. In this context the use of energy storage in parallel to wind farms are a very interesting alternative to make from the wind power a controllable electricity source. In fact there will be necessary to use electricity storage systems to control power balance in areas with high penetration of wind power. The use of a battery gives the chance to store the electricity production peaks, to supply the stored energy when there is not wind power available or when the power consumption is very high and there is the need of extra power source. In this way the use of BESS would avoid the collapse of the network.

The simulations presented have clearly shown that the connection of a battery working in parallel to a wind farm helps the network absorbing the excess power produced by the wind farm during consumption valleys, releasing this power during consumption peaks. This fact also represents benefits for the DG owners because the energy is stored when the prices are low and sold at higher prices. But the actual remuneration system reduces drastically the capability of a BESS to get benefits in the free market, because the larger difference between cheapest prices and most expensive prices for kWh is reduced to 1,4c€/kWh.

Looking at the results of the simulations a first conclusion is obvious, since the shortest amortization time is 120 years; it is not profitable to install a battery in parallel to a wind farm with the actual remuneration system. In this situation the investment of a BESS would be interesting only when the storage is necessary, like in islanded grids with a high penetration of renewable energies.

Since the need of energy storage seems to be necessary in a future electrical grid with a high penetration of renewable energies, it will be necessary to change the policy and give an incentive to DG owners in order to promote the installation of energy storage systems.

B.9. References

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