UNIVERSIDAD PONTIFICIA
ICAI ICADE
COMILLAS
MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD ELÉCTRICA

DESIGN OF A FACTS DEVICE TO IMPROVE THE IMPORTING CAPACITY FROM MOROCCO

Author: Antonio Malpica Morales
Director: Pablo Frías Marín

Madrid
May 2014

AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN ACCESO *ABIERTO* (*RESTRINGIDO*) DE DOCUMENTACIÓN

1º. Declaración de la autoría y acreditación de la misma.

El autor D. ANTONIO MALPICA MORALES, como ALUMNO de la UNIVERSIDAD PONTIFICIA COMILLAS (COMILLAS), **DECLARA**

que es el titular de los derechos de propiedad intelectual, objeto de la presente cesión, en relación con la obra DESIGN OF A FACTS DEVICE TO IMPROVE THE IMPORTING CAPACITY FROM MOROCCO[1], que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual como titular único o cotitular de la obra.

En caso de ser cotitular, el autor (firmante) declara asimismo que cuenta con el consentimiento de los restantes titulares para hacer la presente cesión. En caso de previa cesión a terceros de derechos de explotación de la obra, el autor declara que tiene la oportuna autorización de dichos titulares de derechos a los fines de esta cesión o bien que retiene la facultad de ceder estos derechos en la forma prevista en la presente cesión y así lo acredita.

2º. Objeto y fines de la cesión.

Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad y hacer posible su utilización de *forma libre y gratuita* (*con las limitaciones que más adelante se detallan*) por todos los usuarios del repositorio y del portal e-ciencia, el autor **CEDE** a la Universidad Pontificia Comillas de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución, de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra (a) del apartado siguiente.

3º. Condiciones de la cesión.

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia, el repositorio institucional podrá:

(a) Transformarla para adaptarla a cualquier tecnología susceptible de incorporarla a internet; realizar adaptaciones para hacer posible la utilización de la obra en formatos electrónicos, así

[1] Proyecto fin de grado.

como incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.

(b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato. .

(c) Comunicarla y ponerla a disposición del público a través de un archivo abierto institucional, accesible de modo libre y gratuito a través de internet.

(d) Distribuir copias electrónicas de la obra a los usuarios en un soporte digital.

4º. Derechos del autor.

El autor, en tanto que titular de una obra que cede con carácter no exclusivo a la Universidad por medio de su registro en el Repositorio Institucional tiene derecho a:

a) A que la Universidad identifique claramente su nombre como el autor o propietario de los derechos del documento.

b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.

c) Solicitar la retirada de la obra del repositorio por causa justificada. A tal fin deberá ponerse en contacto con el vicerrector/a de investigación (curiarte@rec.upcomillas.es).

d) Autorizar expresamente a COMILLAS para, en su caso, realizar los trámites necesarios para la obtención del ISBN.

d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

5º. Deberes del autor.

El autor se compromete a:

a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.

b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.

c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.

d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

6º. Fines y funcionamiento del Repositorio Institucional.

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

a) Deberes del repositorio Institucional:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.

- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusiva del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.

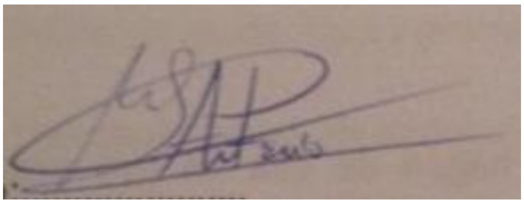
- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.

b) Derechos que se reserva el Repositorio institucional respecto de las obras en él registradas:

- retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 27 de Mayo de 2014.

ACEPTA



Fdo:…………………………

Agradecimientos

A mis padres y mi hermana, por darme la oportunidad y enseñarme a esforzarme cada día al máximo.

A Pablo y Camila, por su dedicación, consejos y ayuda durante la elaboración de todo el proyecto.

A Rafael, Ezequiel y Fernando, porque sin ellos no habría sido posible llegar hasta aquí.

DISEÑO DE UN DISPOSITIVO FACTS PARA MEJORAR LA CAPACIDAD DE IMPORTACIÓN DESDE MARRUECOS

Autor: Malpica Morales, Antonio.

Director: Frías Marín, Pablo.

Entidad colaboradora: ICAI – Universidad Pontificia Comillas.

RESUMEN DEL PROYECTO

La política energética en Marruecos pretende integrar un gran volumen de energías renovables dentro de su mix energético para el año 2020. De este modo, Marruecos pretende reducir parte de la dependencia energética del exterior. La introducción de estas tecnologías renovables va unida al proyecto MEDGRID, cuyo objetivo es instalar grandes centros de producción a lo largo del norte de África y exportar parte de esta producción eléctrica, para satisfacer la demanda europea mediante interconexiones eléctricas en la zona del mar Mediterráneo.

Se ha analizado el flujo previsto para la interconexión eléctrica España – Marruecos, que conecta la zona sur de España (Tarifa, Cádiz) con el norte de Marruecos (Fardioua). El flujo a través de la interconexión ha sido típicamente de España a Marruecos, sin embargo, para el año 2020, se prevé que el flujo de energía eléctrica a través de esta interconexión cambie, provocando que exista un gran número de horas en las que la interconexión alcance valores cercanos al límite (600 MW) para la exportación de energía eléctrica desde Marruecos hasta España.

La red sur de transporte española ha sido diseñada prácticamente para evacuar energía desde la zona norte hasta el sur, incluida la interconexión. El cambio expuesto anteriormente, puede provocar sobrecargas en determinados puntos de la red sur de transporte, que ponga en peligro la continuidad del suministro y la seguridad del sistema. En el escenario que se plantea se ha identificado que aparecen sobrecargas en los dos transformadores (600 MVA) de la subestación de Pinar del Rey (Cádiz).

Una vez se han identificado el número de horas de congestiones y la localización de las mismas, se procede al diseño de un FACTS que permita eliminar las sobrecargas que puedan aparecer en dichos transformadores. Un dispositivo FACTS (Felxible Alternating Current Transmission System) es un equipo eléctrico que puede controlar y modificar ciertos parámetros eléctricos del sistema de transporte con el objetivo de mejorar la flexibilidad y capacidad del mismo.

La instalación del FACTS permitirá integrar la energía importada desde Marruecos de forma más segura, incrementando así la capacidad de interconexión de España con el exterior. El dispositivo FACTS escogido en este proyecto es un OLC (Overload Line Controller), que permite cambiar la reactancia del elemento al cual está conectado, en este caso los transformadores, con el fin de variar el flujo de potencia activa. El OLC

está compuesto de tres reactancias en serie con sendos interruptores en paralelo, el valor obtenido de las reactancias para este caso ha sido de 0,2 Ohms por cada escalón y una potencia reactiva nominal de 36 MVAr.

Por último la justificación económica del FACTS requiere del análisis de costes y beneficios. El coste de inversión en el dispositivo FACTS ha sido estimado en 1.800.000 €. Al mismo tiempo, la instalación del FACTS permitirá reducir los costes de operación del sistema eléctrico español, evitando los redespachos. Los redespachos consisten en operaciones destinadas a reducir sobrecargas que puedan producirse en el sistema eléctrico. Dicha operación consiste en reducir generación convencional de unidades cercanas a las sobrecargas, con el fin de aliviarlas. Debido a que debe existir un balance constante entre generación y demanda en todo momento, la generación que se ha reducido, debe ser suministrada por otra unidad que no había entrado previamente en el mercado y, por tanto, su coste asociado será mayor que el de la primera unidad reducida.

DESIGN OF A FACTS DEVICE TO IMPROVE THE IMPORTING CAPACITY FROM MOROCCO

ABSTRACT

Energy policy in Morocco aims to integrate large amounts of renewable energy in its energy mix by 2020. Thus, Morocco tries to reduce part of external dependence energy. The introduction of these renewable technologies is joined together to MEDGRID project, which aims to install large production centers throughout North Africa and export of electricity production to meet European demand by electrical interconnections in the Mediterranean Sea.

It has been analyzed the flow through the electrical interconnection Spain - Morocco that connects the south of Spain (Tarifa, Cádiz) with northern Morocco (Fardioua). The flow through the interconnection has been mostly from Spain to Morocco, however, by 2020, it is expected that the flow of electricity through the interconnection changes, due to the existence of a large number of hours, which interconnection reach close to the limit value (600 MW) for electricity exports from Morocco to Spain.

The southern Spanish transmission network has been designed practically to evacuate electrical energy from the north to the south, including interconnection. The change above can cause overloads at certain points of the southern transmission network, which endangers the reliability of the power system, including the continuity of supply and adequacy. In the presented scenario, overloads appear in the two transformers (600 MVA) substation in Pinar del Rey (Cádiz).

Having indentified a number of hours of congestion and location thereof, it is proceed to the design a FACTS device allows relieving the overloads that may appear in these transformers. A FACTS (Flexible Alternating Current Transmission System) is an electrical device that can control and modify certain electrical parameters of the transmission system in order to improve the flexibility and the capacity thereof.

Installation of FACTS will integrate imported energy from Morocco safer, increasing the interconnection capacity between Spain and abroad. The FACTS device chosen in this project is an OLC (Line Overload Controller) that allows changing the reactance of the element which it is connected, in order to vary the active power flow. The OLC is composed of three reactances in series with individual switches in parallel, the values obtained from the reactance for this case has been 0,2 Ohms per step and a rate reactive power of 36 MVAr.

Finally, the economic justification of FACTS device requires the cost and benefits analysis. The investment cost of FACTS device has been estimated at 1.800.000 €. At the same time, the installation of FACTS will reduce the operating costs of the Spanish electricity system, avoiding redispatches. The redispatches consist of operations to reduce overloads that may occur in the electrical system. Such operation is to reduce conventional generation of units close to the overload, in order to alleviate them.

Because there must be a constant balance between generation and demand at all times, the generation that has been reduced, must be supplied by another unit that had not previously entered the market and therefore the associated cost will be greater than that of the first reduced unit.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

Chapter 1 INTRODUCTION

The objective of this project is to design a FACTS device to improve security of electricity supply in scenarios of high import electricity from Morocco.

A FACTS is an electrical device that can control certain parameters of the electricity transmission system in order to improve the flexibility and capacity thereof.

For 2020 Morocco is expected to be able to manage a great amount of renewable energies, mainly wind, hydro and solar, in its generation mix. This increase in installed capacity, coupled with MEDGRID project that aims to install large production of solar power throughout North Africa, enabling the transport of large amounts of electricity to Europe to supply electricity demand.

To evacuate the electricity is used the electrical interconnections, which connect different electrical systems to exchange electricity. Currently the only existing electrical interconnection between North Africa and Europe is the interconnection between Tarifa (Spain) and Fardioua (Morocco), consisting of two submarine cables with a transmission capacity of 700 MW each.

Flow through the electrical interconnection between Spain and Morocco has typically been exporting from the Spanish point of view. However, the facts stated above, in 2020, the normal flow through the interconnection will be affected; making Morocco is able to export large volumes of electricity for some time.

Southern Spain's transmission network has been designed to basically evacuate power flows from north to south, although by 2020, flows by electrical interconnection may modify the typical power flow. At this overload may occur in lines or transformers of the transmission network, putting the stability of the power system at risk.

The FACTS device chosen for this project has been a FACTS called OLC (Overload Line Controller). This device consists of three reactors in series, controlled by parallel switches that let it add or remove steps reactance. The switches are automated by a control system which operates according to the condition of the network.

The objective of this FACTS is basically, being able to increase or decrease the reactance of the element which is connected in order to vary the active power flowing through the element. Therefore, when a line or a transformer, which the FACTS is attached, is in an overload situation, the FACTS acts increasing the reactance (since the active power transmitted can be considered inversely proportional to the reactor) and the overhead is reduced .

The introduction of FACTS in the southern network will allow:

- Increase the safety of the electrical system, as it will reduce the effects of surges occurring in the transmission network.

- Embed a greater amount of energy coming from Morocco, increasing the number of hours in which the interconnection capacity may be close to its maximum value.

Because FACTS devices are relatively new, the manufacturing cost is rather high. Therefore, a power flow analysis of southern Spain's transmission network will be performed in order to identify the best location to install a single FACTS.

Installation of FACTS, also provides positive aspects as economic and environmental terms is concerned. Given that all the electricity that is imported from Morocco, will be principally renewable energy source and it need not be supplied from the Spanish electricity system. This will save fossil fuels with consequent environmental benefits it brings.

When an overload occurs in the electricity transmission system, the operating procedures of the Spanish TSO (Transmission System Operator) conducted variations in the location of the generation, called redispatches. Redispatches involve decreasing generation from nearby power plants to overloads, so it is achieved that the overload disappears. However, as a balance must be maintained at all times between generation and demand, it is necessary that TSO operate or raise the set point of another generation power plant to power the same value that was previously reduced.

These redispatches involve a high economic impact within the Spanish electricity system, with the installation of FACTS, part of these redispatches can be avoided, since the FACTS device that has been used will instantly reduce such overloads, as it was mentioned before.

1.1 OBJECTIVES

The main objectives pursued in this project are:

- Brief study on the introduction of renewable energy in Morocco and impact MEDGRID 2020. Be able to analyze the proposed objectives for the year 2020 and analyze the impact of the introduction of this type of energy referring to electrical interconnection between Spain and Morocco. It is created a load curve that reflects the net balance of energy exchanged through the interconnection for each hour of the year.
- Localization of the best place for installing the FACTS. Analyzing the power flows on the transmission network south Spain with data obtained in the load curve described in the previous paragraph, the state of the network is obtained for different demand scenarios in southern Spain. With this data, it is selected the best emplacement, in order to install the FACTS device. Because typically the power flows in this area have always been to Morocco, aims to highlight the surges that may appear on overhead lines or power transformers when a large amount of electricity is imported from Morocco.

- Technical characteristics of the FACTS device. It is necessary to determine the technical characteristics that the FACTS device has to have, such as the reactance value, the reactive power, son on. These characteristics will allow the proper functioning of the device in order to relive the possible contingences may occur.
- Economic study. Justification for the installation of FACTS, analyzing investment in such equipment. With the installation of such equipment is to avoid the redispatches and associated cost thereof.

1.2 MOTIVATION

Today's society is more and more aware of the use and utilization of available resources, environmental problems around him and legacy to future generations. In this context, there is many projects to improve the facilities and infrastructures, as well as trying to increase the efficiency of processes and services.

This project conducted a baseline study that attempts to apply the above, since its main objective is to try to improve or make an existing infrastructure more efficient, such as to improve the network of transport south of Spain. Moreover, it is pursued the increase of security to the electrical system, ensuring continuity of supply

First, the knowledge and the integration of renewable energy into the power system, in this case the electrical system of Morocco, is one of the main motivations for carrying out the project. There are a number of issues that have been given special attention in this project, such as the interest to know more about the generation profiles of each type of renewable energy, or be able to analyze how regulation and decision making on energy help change the outlook of an electrical generation system.

The FACTS are devices integrated into new technologies to improve the current electricity grids, to form part of what are known as smart grids. This new technology highlights by the great development carried out in recent years and the amount of studies and research projects with various equipments based on this technology.

Understanding electric power systems and in particular, the power transmission through power lines have been an essential role to carry out the project. Being able to understand how the FACTS changes the power flow has been another task of particular interest within this project.

Chapter 2 INTERCONNECTION STUDY

2.1 INTRODUCTION

The objective of this section is to analyze the flow by the electrical interconnection flow in 2020. For this year, it is expected that the Moroccan energy policy introduces a large amount of renewable energy, which together with the MEDGRID project, causes a change in the typical power flow through the interconnection. This change means that it could be some hours where the energy delivery was from Morocco to Spain, with the possible consequence it may have in the transmission network south Spain. So the aim is to obtain a load curve that reflects the net balance of energy exchange between Spain and Morocco for 2020.

2.2 METHODOLOGY

First of all, it will do a search about Moroccan targets for renewable energies for 2020, compiling information about type of energy and power installed. In addition, information about MEDGRID project will be obtained, specially installed generation and the possible interconnection between North Africa and Europe. With this data and the demand forecast, it will be made the estimated profile of the electrical interconnection for 2020.

Moreover, at the same time that interconnection study is performed, it will be studied the electrical demand of southern Spain, in order to use these results later.

2.3 CURRENT SITUATION

The electrical interconnection between Spain and Morocco consists of two submarine cables connecting the “Estación Terminal Estrecho” (Cadiz, Spain) with “Ferdioua” substation (Morocco). The nominal voltage at which the energy exchange is produced is 400 kV and the transport capacity of each submarine cable is 700 MW.

The following table demonstrates the annual net balance for interconnection between Spain and Morocco, taken from the 2013 Advance Spanish electricity system (REE, 2013). Positive data refer to an export balance from the point of view of Spain.

Year	Spain - Morocco (GWh)
2009	4.588
2010	3.903
2011	4.495
2012	4.900
2013	5.364

Table 1: Annual net balance for electrical interconnection Spain - Morocco.

As seen in the table above, the net flow interconnection has always been from Spain to Morocco. The number of hours the interconnection flow was from Morocco to Spain, as well as the energy transmitted by the interconnection has been very small. For example in 2013, all the energy imported by Spain from Morocco was only 1 GWh, compared with 5.365 GWh were exported from the Spanish side.

This is because the current Moroccan electrical system needs external support in order to satisfy the entire electrical demand. The Moroccan power system focuses much of its conventional power generation technology using fossil fuels such as coal or gas. This technology represents 69.6% of the generation mix (Branche Electricité - Bilan des Activités, 2012)

Technology		Installed power (MW)	Percentage
Hydraulic		1.306	19,56
Pumping		464	6,94
Thermal	Fuel	600	8,98
	Coal	1.785	26,74
	Gas turbine	1.215	18,19
	Diesel	202	3,03
	Combined cycle	850	12,38
Wind		255	3,82

Table 2: Electric generation mix in Morocco in 2012.

The production of electricity in Morocco in 2012 was 26.495,5 GWh, of which 23.812,3 GWh were produced by thermal power plants. If the Moroccan national production is added the imported energy from Spain (4.898,1 GWh) and subtract the energy exported to Algeria (56,8 GWh), the total power demand of the same year is obtained, resulting in a total of 31.055,6 GWh. This reflects the large energy dependence on fossil fuels and the need for external support for Morocco to be able to supply its own electrical demand.

2.4 MOROCCAN ENERGY PROGRAMME FOR 2020

The resulting industrial and economic development that is experiencing Morocco necessitates investment in power plants that increase the capacity of the Moroccan electricity system. In this context, Morocco is pursuing an energy policy designed to install large amounts of renewable energy to ensure power supply, while reducing emissions (Le Maroc, pays des energies renouvables, 2010).In 2010, the Renewable Energy Law 13-09 was passed, with the objective of improve the regulation of the generation and commercialization in this type of alternative energy (El sector de la energía solar y otras energías renovables en Marruecos, 2010).

Since the adoption of the aforementioned law, two projects were developed to achieve the objectives:

- Moroccan Solar Plan: By 2020, it has as main objectives to build 5 solar thermal power plants with a total installed capacity of 2.000 MW.
- Integral Wind Power Production Program: Install 2.000 MW of wind power by 2020.

Also in 2020, Morocco aims to obtain 6.000 MW of electricity from renewable energy sources, these 6.000 MW will compose 42% of the generation mix, in the following table shows the energy mix expected by 2020:

Technology	Installed power (MW)	Percentage
WInd	2.000	14
Solar (CSP)	2.000	14
Hydraulic	2.000	14
Coal	3.857	27
Fuel	1.428	10
Gas	3.000	21
Total	14.285	100

Table 3: Energy mix expected in Morocco by 2020.

If technological mix forecast for the year 2020 with the year 2012 is compared, significant changes are observed. First, the increase in renewable energy, target mentioned above. However, due to the variability of renewable energy, coupled with the difficulty in forecasting this type of energy, it is necessary to have a system of support or backing to be able to supply the required power when renewable energies are not capable of produce. This system will be composed mainly by combined cycle plants, which is why it also increases the weight of the gas in the electricity generation mix by 2020.

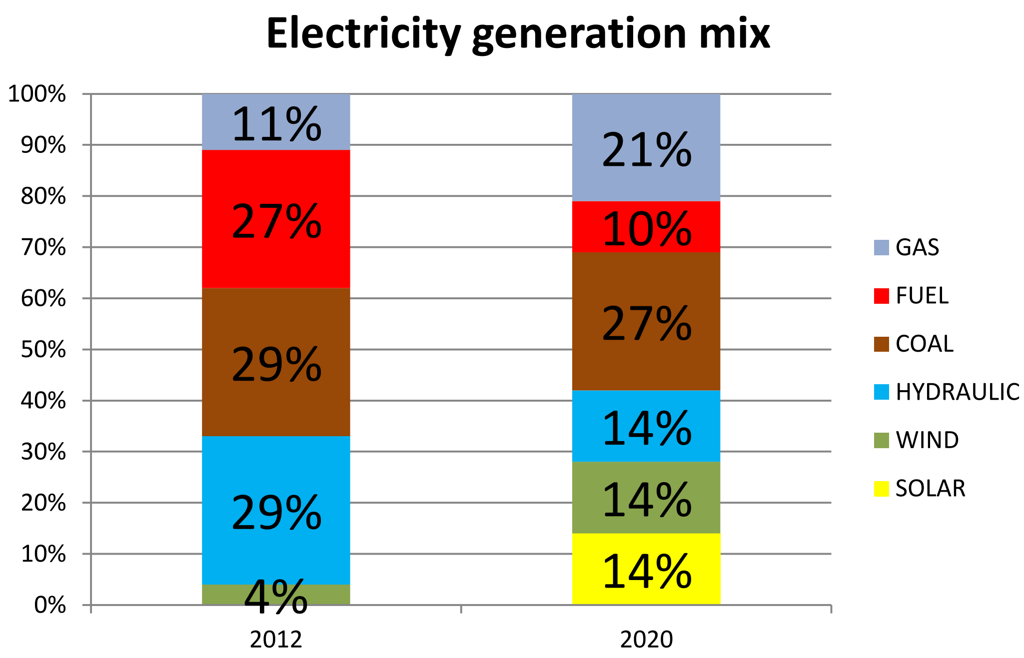


Figure 1: Electricity generation mix in Morocco.

2.4.1 SOLAR ENERGY IN MOROCCO

Morocco has a privileged environment for the production of solar energy, with more than 3.500 hours of sunshine per year and an average solar radiation of 4,7 kWh/m^2/day in the north of the country and 5,6 kWh/m^2/day in the south. In addition 30% of the territory is exposed to an annual solar radiation of 2.000 kWh/m2.

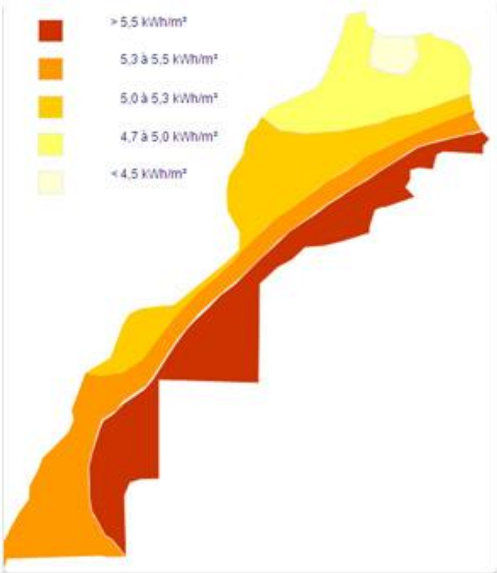


Figure 2: Solar radiation in Morocco.

In recent years, solar energy has been harnessed in Morocco by installing photovoltaic panels to supply electricity to remote rural areas, thus avoiding connect these rural communities with the electric power grid. Therefore, these solar panels are not taken into account in the national electricity production.

Thanks to the Moroccan Solar Plan, 5 large solar thermal plants will be developed that will constitute the 2.000 MW of installed capacity. The following table lists the location, installed capacity and estimated annual production per power plant (El sector de la energía solar y otras energías renovables en Marruecos, 2010):

Location	Power (MW)	Estimated production (GWh)
Ouarzazate	500	1.150
Aïn Béni Mathar	400	835
Forum Al Ouad	500	1.150
Cabo Bojador	100	230
Sebkhate Tah	500	1.040

Table 4: Solar thermal power plants in Morocco 2020.

The technology used in this type of solar thermal power plants will be mainly parabolic trough, known as CSP (Concentrating Solar Power), this technology also allows accumulating the heat from solar radiation, over a period of time. Thus the production of these plants may be kept for a few hours after the sunlight stops reaching the parabolic trough.

2.4.2 WIND ENERGY IN MOROCCO.

The following figure shows the average wind speed in the Moroccan territory:

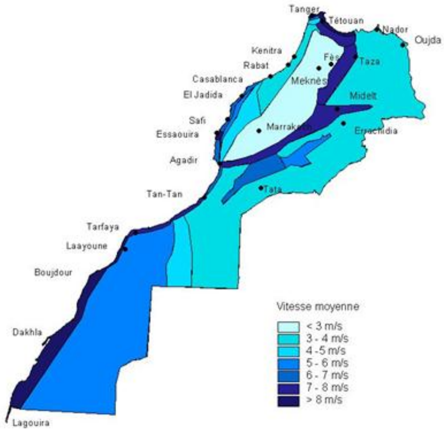


Figure 3: Average wind speed in Morocco.

Wind power currently installed in Morocco is 287 MW, divided into 3 wind farms. These 287 MW would have to add 720 MW of wind farms under construction expected to operate throughout 2014, and the remainder to reach 2.000 MW will come from 6 wind farms to be built during the period between 2014 and 2020. Then, the location and power of each future installation is specified:

Location	Installed power (MW)	Opening
Tarfaya	300	2014
Akhfennir	200	2014
Laâyoune	50	2014
El Haouma	50	2014
Jbel Khalladi	120	2014
Tanger II	100	2014-2020
Taza	150	2014-2020
Midelt	150	2014-2020
Jbel Lahdid	200	2014-2020
Tiskard	300	2014-2020
Boujdour	100	2014-2020

Table 5: Wind farms in Morocco.

2.4.3 HYDROPOWER IN MOROCCO.

Today there are 27 hydropower plants in Morocco constitute an installed capacity of 1.036 MW. To get reach 2.000 MW, it will be built in the 2014-2020 period small hydroelectric plants. It is this type of technology which is considered within renewable energy, while large hydro (power > 12 MW) is excluded from the group of alternative energy as far as economic and regulatory incentives are concerned.

These small hydroelectric plants will be dispersed throughout the Moroccan territory, with about 200 potential sites. The maximum power allowed for some of these sites is 100 kW and a minimum of 15 kW.

2.5 MEDGRID

The MEDGRID Project is part of the three energy targets set by the EU for 2020. These objectives are:

- Reduce by 20% greenhouse gas emissions compared to 1990 levels.
- Increase to 20% the share of renewable energy in final energy consumption.
- Save power consumption by 20% through measures and structural changes.

This project is composed by companies, transmission and distribution of electrical energy, expert companies in infrastructure financing and other services to climate change. MEDGRID works, therefore, with public authorities in the countries involved, the European Commission, the scientific community and investment banks, among others.

To achieve the above objectives, the MEDGRID project has created two programs involving the countries of northern, southern and eastern Mediterranean to work in a cooperative energy strategy. The first program is the creation of an energy network of electrical interconnections, while the second, the Mediterranean Solar Plan, promotes cooperation between countries on both sides of the Mediterranean in renewable energies.

This latter launched in 2008 a program that anticipated the installation of 20 GW of renewable energy throughout North Africa by 2020, due to the high solar and wind potential which owns the area (Coast Morocco, Sahara Desert , etc.). Part of the 20 GW, 5 GW specifically, will be exported to Europe to make solar plants in the Sahara profitable.

The electrical interconnections, that allow transport electricity to Europe to meet electricity demand, will be located in the Mediterranean and will be part of the facilities developed by the first program MEDGRID project. The following figure represents possible electricity production centers and their electrical interconnections:

Figure 4: Electrical interconnections expected by the project MEDGRID.

The main considered problem is that the only currently existing interconnection between North Africa and Europe is the electrical interconnection between Spain and Morocco. It is expected that by 2020, it remains the only available interconnection with a capacity of 1.400 MW, which is not enough for what is sought with MEDGRID project.

Among the studies MEDGRID project carried out, can be found the following objectives (MEDGRID, 2010):

- Technical and economical design of Mediterranean network enabling transmitting those 5 GW to Europe.
- Creating a common regulatory framework to encourage investment and the establishment of economic incentives, fees, so on.
- Demonstrate the impact on economic growth.
- Promote European industries and technologies, especially renewable energy and transmission high voltage direct current lines (HVDC).

2.6 STUDY OF GENERATION, DEMAND AND INTERCONNECTION.

After the preliminary analysis of the situation of the electricity sector in Morocco in 2020, then it will be presented data from a study of the load profile of the electrical interconnection between Spain and Morocco, for the same year.

The interconnection profile contains 8784 values corresponding to each hour of the 2020. Every hour of the day has been classified with a label indicating whether it was a time corresponding to peak, plain or valley time. This distinction has been used for the subsequent economic analysis. The following table indicates the distinction made, also distinguish between summer and winter.

Type	Summer	Winter
Valley	0:00 - 8:00	0:00 - 8:00
Plain	8:00 - 11:00 y 15:00 - 0:00	8:00 - 18:00 y 22:00 - 0:00
Peak	11:00 - 15:00	18:00 - 22:00

Table 6: Peak, plain and valley time for summer and winter.

Each value of the profile is obtained by a balance between generation and demand for that hour. Both generation and demand have been calculated based on generation and demand profiles in Spain, but scaled to the predicted values for Morocco in 2020.

The generation has been divided into two large groups, first produced by the renewable energy and the other corresponding to the conventional thermal generation including secondary reserve at all times has to keep the balance between generation and demand.

Renewable generation is in turn divided into the wind energy (2.000 MW of installed capacity), hydropower (2.000 MW) and solar energy, which consists of the production of CSP plants in Morocco (2.000 MW) and a part of the MEDGRID project. To estimate the MEDGRID project, it is assumed that there are only 5.000 MW of installed capacity from solar power (CSP).

Each of the above technologies has been scaled for the aforementioned power values, as base profiles were used actual data generation in Spain in 2010. Wind, hydro and thermal generation have been obtained from the data published by "Red Eléctrica" (ESIOS, 2010). Because solar radiation is slightly higher in Morocco than in Spain, for the values obtained from CSP technology production, they have increased by 10%.

Conventional thermal generation is set as 45% of total renewable energy, i.e. the Moroccan electrical system must have at all times an additional generation that is able to serve as backup 45% as secondary reserves. This heat generation is primarily from coal and combined cycle as well as fuel.

In the following table is summarized each technology generation and total generation after 2020.

	Renewable				Thermal
	Wind	CSP Morocco	MEDGRID	Hydro	
Installed power (MW)	2.000	2.000	5.000	2.000	7.428
Generation (GWh)	7.872,45	2.399,36	5.998,41	2.258,04	20.647,47

Table 7: Types of technology for generating study.

Electricity demand is calculated using the annual profile of electricity demand in Spain in 2012. Such profile is scaled to the total electricity consumption in Morocco for the same year and subsequently estimated electricity demand in 2020, applying a rate demand growth of 5% annually (ICEX, 2012).

The following table shows the total demand in 2012 and the forecast for 2020 and peak demand each year:

	2012	2020
Total demand (GWh)	31.055,6	45.883,2
Peak demand (MWh)	5.280	7.795

Table 8: Comparison Moroccan electricity demand in 2012 and 2020.

Once the generation and demand profiles are established, the flow through the interconnection is calculated using the following formula:

$$INT = (RES + SEC.GEN) - LOAD$$

Equation 1: Interconnection flow.

Where INT is the flow through the interconnection, RES refers to the total amount of energy generated by renewable energies. SEC. GEN is the conventional thermal generation or secondary reserve, next to RES form the whole generation. Finally LOAD is the electricity demand.

If the total generation is greater than demand, the INT term is positive; this implies that Morocco exports energy through electrical interconnection. However, if the demand exceeds generation, INT is negative, meaning that Morocco needs to import electric power through interconnection to satisfy electricity demand.

Below, there is a graph representing the load profile of the interconnection by 2020. The 8784 values have been ordered in decreasing order, and it has not taken into account any technical restrictions.

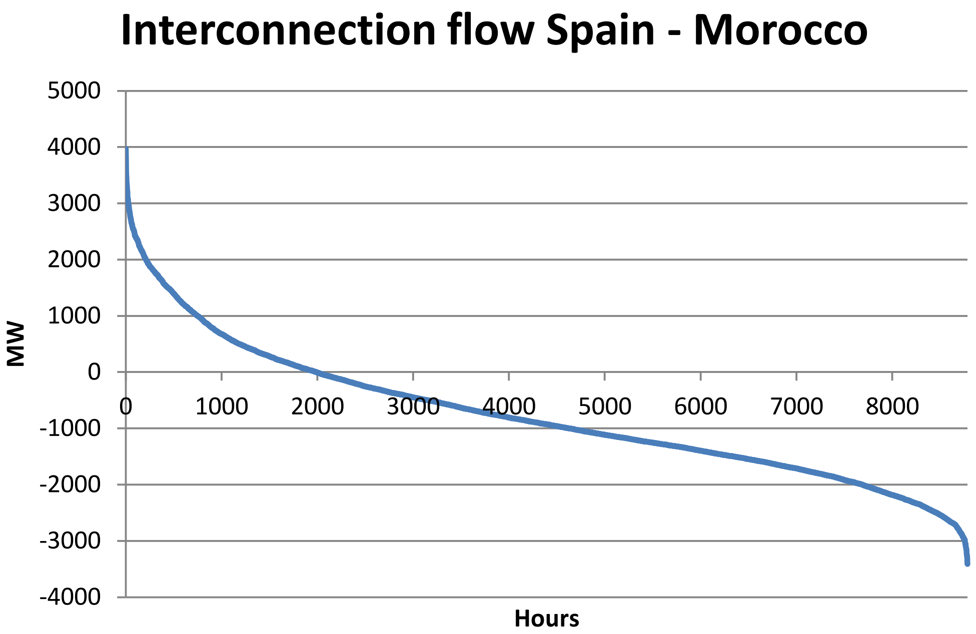


Figure 5: Load curve for electrical interconnection between Spain and Morocco 2020.

On the vertical axis it is represented the hours, while the horizontal axis the net energy that flows through the interconnection is shown. Positive values correspond to flow through the interconnection of Morocco to Spain, and negative values to energy flow from Spain to Morocco.

Due to technical restrictions existing in interconnection (maximum capacity of 1.400 MW) and existing technical constraints also on both sides of the interconnection (real transport capacity 900 MW when the flow is from Spain to Morocco and 600 MW when the flow is from Morocco to Spain), the curve is presented above is modified. Therefore, all those values that exceed the limits are reduced to the same limit, leaving the curve as follows:

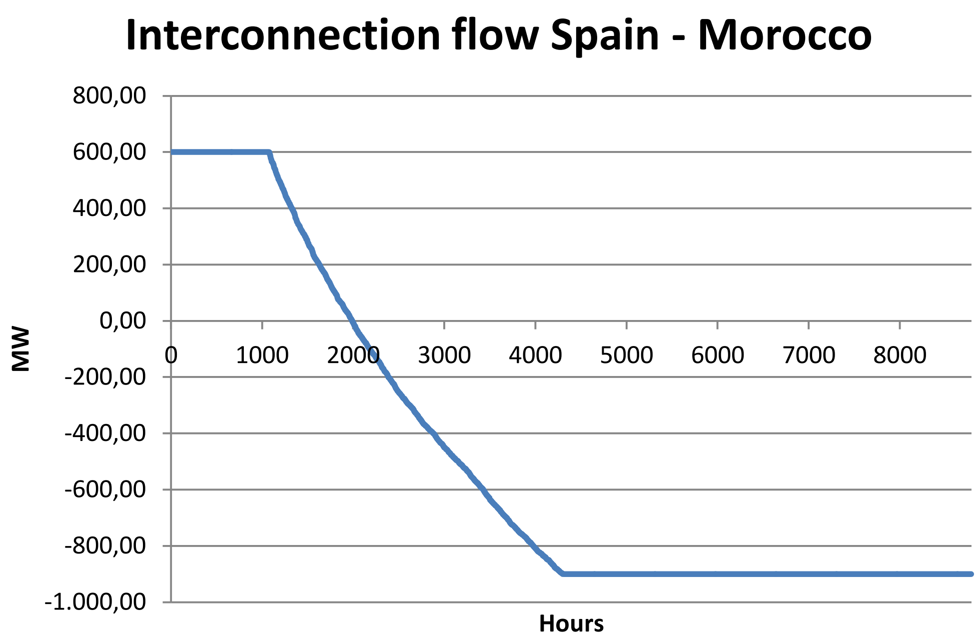


Figure 6: Electrical flow interconnection Spain - Morocco 2020 with existing technical constraints.

The most important data that is extracted from the previous curve is that there will be approximately 1075 hours in 2020 in which the flow through the interconnection is at the boundary. During these 1075 hours, Spain will be importing electricity from Morocco; specifically 600 MW will not be needed to supply power plants within the Spanish territory, with consequent savings involved.

Southern Spain's transmission network was configured to transmit power flows from north to south. The significant increase in the number of hours that Spain imports electric energy from Morocco, can cause overloading of lines and transformers of the Spanish transmission system. These overloads can occur, especially when the flow through the interconnection of Morocco to Spain, is near its limit 600 MW.

For further analysis of the overloads has also conducted a study of the electricity demand in the south of Spain, because overloads are presented in scenarios in which the flow was 600 MW through interconnection (from Morocco to Spain) and demand in the southern region was high (over 6.000 MW).

To forecast demand, first it has obtained the data of the hourly electricity demand in Spain in 2012, then it has generated the profile of Spanish demand in 2020, using a growth rate of 2% (ENTOS-E, 2013). When it has obtained the demand profile for Spain, the profile for the southern zone is calculated, this profile was calculated by relating the peak demand of the south and in Spain. In 2012, the peak demand in the south was a 17.38% of peak demand in Spain. The following table details the total demand and peak in Spanish and south in 2012 and the forecast for 2020.

	Spain 2012	South 2012	Spain 2020	South 2020
Total demand (GWh)	251.389	4.735	294.543	5.548
Peak demand (MWh)	42.813	7.441	50.162	8.718

Table 9: Comparison between electricity demand in Spain and south in 2012 and 2020.

2.7 RESULTS

The results might be useful for the next sections are the following:

- There will be approximately 1075 hours, in which the flow through the interconnection will be 600 MWh (the maximum value allowed from Morocco to Spain).
- The total demand in the south of Spain for 2020 has been estimated in 5.548 GWh.

2.8 CONCLUSIONS

By 2020, the Moroccan energy outlook will change significantly, planning undertaken to introduce a significant amount of renewable energy (6.000 MW) joined to the progressive integration of MEDGRID project will allow Morocco to mitigate some of the power dependence outside. Similarly there will be certain times when the Moroccan electricity production allows export large amount of energy to Spain, changing the power flow profile for interconnection. Specifically, it is estimated to be about 566 hours in which the flow of electrical interconnection is 600 MW from Morocco to Spain, with the consequences it may have in the operation and control of Spanish transmission network.

Chapter 3 LOCATION OF FACTS

3.1 INTRODUCTION

The objective of this section is to carry out a technical study of the transmission network that allows determining the best location for the installation of the FACTS device. It will be studied different scenarios of power flow in order to observe the surges that may affect the network when the import of electricity from Morocco is high. When the overloads were located, the best location for the FACTS device will be chosen.

A FACTS (Flexible Alternating Current Transmission System) is a device for controlling the flow of power flowing through a system by increasing the capacity and flexibility of it. Consequently, the FACTS will be able to manage with the possible overloads occur in the southern Spanish transmission system.

Once the location has been selected, it will be necessary to determine the main features of the FACTS that allow eliminating the overloads, in addition it will be explained the functioning of the device.

3.2 METHODOLOGY

The power flow is created using the PSS/E® program. Using PSS/E®, it has been modeled the whole transmission network in Spain. In it are included the 400 kV and 220 kV lines, transformer substation 400 kV-220 kV, and have also added some important demand nodes. In addition to the transmission network has been necessary to include the generators of the main power plant of the Spanish electricity system with their respective step-up transformers, which allow connecting to the Spanish transmission network.

It has also created a display window of the southern transmission network. This window allows obtaining the charge level of each of the network elements and is easier to see the overloads.

Finally, it has also been very important, try to model the electrical interconnection Spain - Morocco. What matters is the amount of power that is injected in the interconnection, for this reason, on the Moroccan side of the interconnection has placed a generator, which simulates the active power injected in the interconnection from the Moroccan side.

For each scenario, possible contingencies that may occur in the south will be evaluated, such as the loss of overhead lines or transformers, just as any maintenance to be performed on the network will be considered, resulting in disconnection of the elements. The aim to evaluate these potential eventualities will be to detect overloads that may occur and how to analyze the optimal location of FACTS device to alleviate such overloads.

The next step is to identify the weakest point of the transmission networks, affected for the surges. When it was identified, the FACTS will be introduced, simulating the effect of the device into the power flow, and observing how the overloads are eliminated.

3.3 INPUT DATA

The input data for this section are the following:

- Spanish transmission network, modeled with the PSS/E®.
- Interconnection flow from Morocco to Spain: 600 MW.

3.4 POWER FLOW

The different power flow scenarios have been created with a common feature: 600 MW of power to be injected from the Moroccan side of the interconnection. This is due to the high number of hours in which this occurs, as it was obtained from the interconnection study. For each scenario, it has been changing demand in the south of Spain, to see how this parameter affects overloads.

Once each stage has set the level of demand in the south and the 600 MW through the interconnection, the power flow is run. According to the operating procedures of Spanish TSO, permissible levels of network load (REE PO 1.2, 1998), it should be considered a series of contingencies in the safety analyzes. These contingencies are known as N-1 criterion, and the power flow must be performed again considering the failure of any of the following elements: generator, line, transformer or reactance.

Additionally it should also be checked the power flow considering simultaneous failure of the two circuits of the double circuit lines that share pylons along more than 30 km of the trail.

Following these operational criteria, it has been evaluated the power flow scenarios, and it has found overloads in the two 600 MVA transformers substation (400 kV - 220 kV) of Pinar del Rey (Cádiz). Then the exact location of the substation is shown, within the southern transmission network:

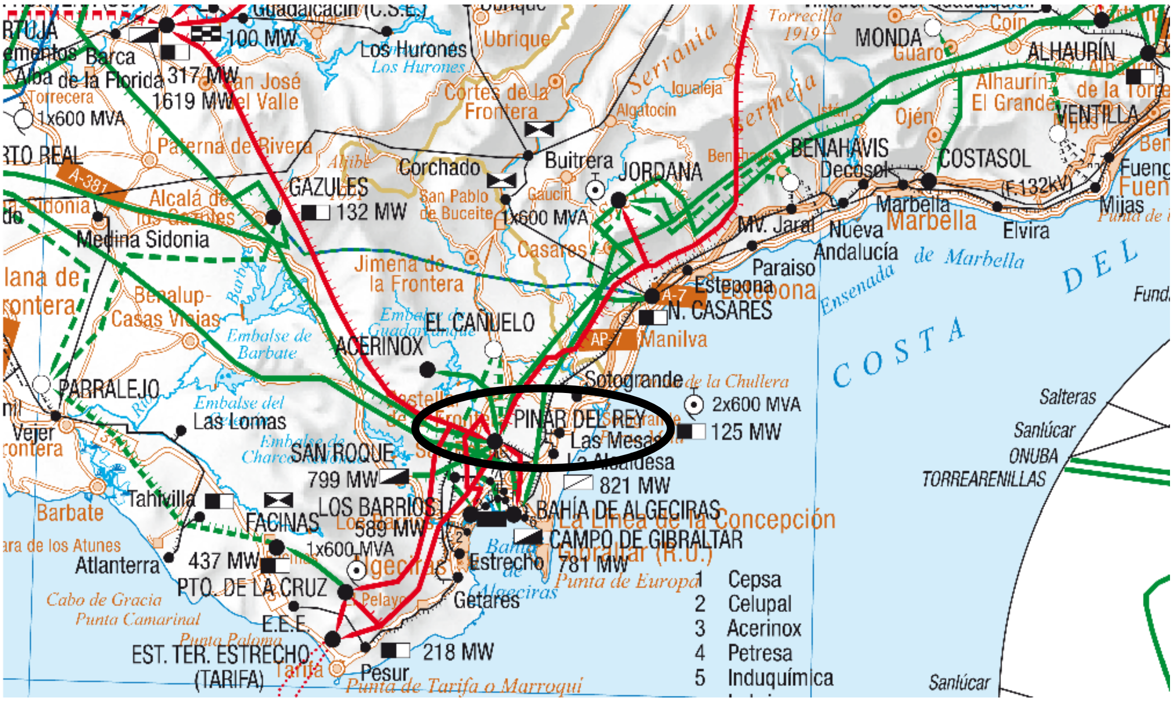


Figure 7:Location of Pinar del Rey substation.

The overloads in the substation occur under the following conditions:

- Power injected in the interconnection from: 600 MW.
- Demand in the southern area exceeding 6.000 MW.
- Simultaneous loss of double circuit line Pinar del Rey - Jordana and double circuit line Pinar del Rey - Tajo de la Encantada, because both lines share pylons.

Depending on the level of demand in the area, thus will be the overloads on transformers. Later in the results section, it is included a table lists the overloads that occur in the two transformers at different demand levels:

Then, the best location for the FACTS device in order to eliminate these overloads is in Pinar del Rey substation, the FACTS will be installed between the output of both transformers and 220 kV bus bars substation.

3.5 FACTS CHARACTERISTICS

The FACTS device selected in the project is called OLC (Overload Line Controller), and belongs to the series FACTS devices. This FACTS has been designed to be installed with high voltage power lines in order to reduce overload them.

However, as discussed in section [3.4], it was explained that the optimal location for FACTS was with the two power transformers substation in Pinar del Rey (Cádiz). The OLC in this case will be coupled to two transformers instead of a transmission line. As the operation of the device is indifferent to the element which is connected and the effect achieved is the same, there is not any problem installing FACTS device in the substation.

The main characteristic, for which it has chosen the OLC, is fast when controlling the flow of active power. Then, it is introduced the formula relating active power transmission between two nodes, with the electrical parameters of the line or element linking these two nodes.

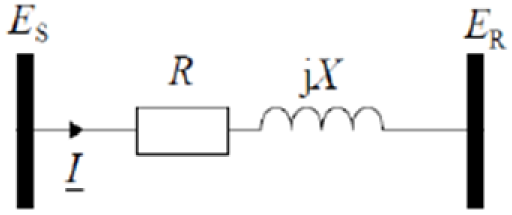


Figure 8: Electrical nodes (S and R) connected via a line.

$$P_{SR} = V_S \cdot V_R \cdot \frac{X}{R^2 + X^2} \cdot sen\ (\delta_S - \delta_R)$$

Equation 2: Active power transmission between two nodes S and R.

Where:

P_{SR}: active power flowing from node S to R.

V_S: node voltage S.

V_R: node voltage R.

X: reactance of the line connecting the node S and R.

R: resistance of the line connecting the node S and R.

δ_S: node electrical angle S.

δ_R: node electrical angle R.

If the line resistance is discounted, since it is less than the reactance of the same, the above expression becomes:

$$P_{SR} = \frac{V_S \cdot V_R}{X} \cdot sen\ (\delta_S - \delta_R)$$

Equation 3: Active power transmission between two nodes S and R, discounting the resistance.

Then, the active power flow between two nodes can be changed, through three basic ways:

- The first, varying the voltage of both nodes (V_s y V_R).
- Second, modifying the line reactance.
- Third, varying the electrical angle of the nodes.

This approach is equally valid, if instead of being a power line which connects the node S and R, is a power transformer, because the electrical model of a transformer reactance is greater than the resistance of the windings presented. Therefore, when working with the OLC, the features which work are the same.

The OLC consists of three reactors in series that are activated or deactivated by switches in parallel; each switch is operated by a control system. Thus the FACTS device is able to modify the reactance of transformers to reduce power surges that occur. A schematic representation of the device is included in the following figure:

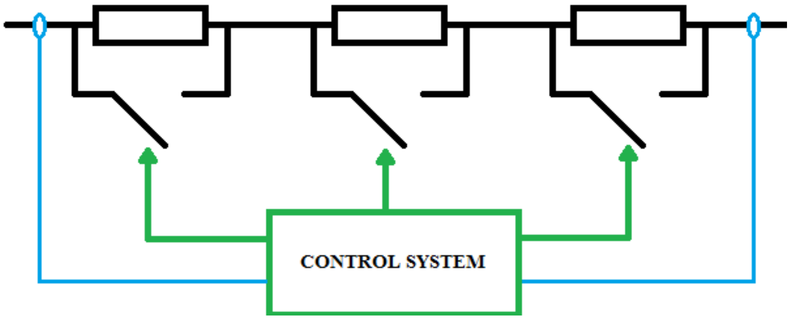


Figure 9: OLC device.

According to equation [3], if the FACTS device allows increasing the reactance of the transformers, the flow of active power flowing through the transformer reduces and therefore the overloads that may have disappear.

This OLC device provides certain novel features such as the speed at the time to act before contingencies, flexible and fast control of reactance, control of reactive power flow and a cost effective solution compared to the PST (transformer power shift) and TCSC (Thyristor controlled series capacitor).

3.6 REACTANCE VALUES

To determine the value of the reactance, has established a routine that would obtain the value of the reactance to eliminate all possible overloads to appear:

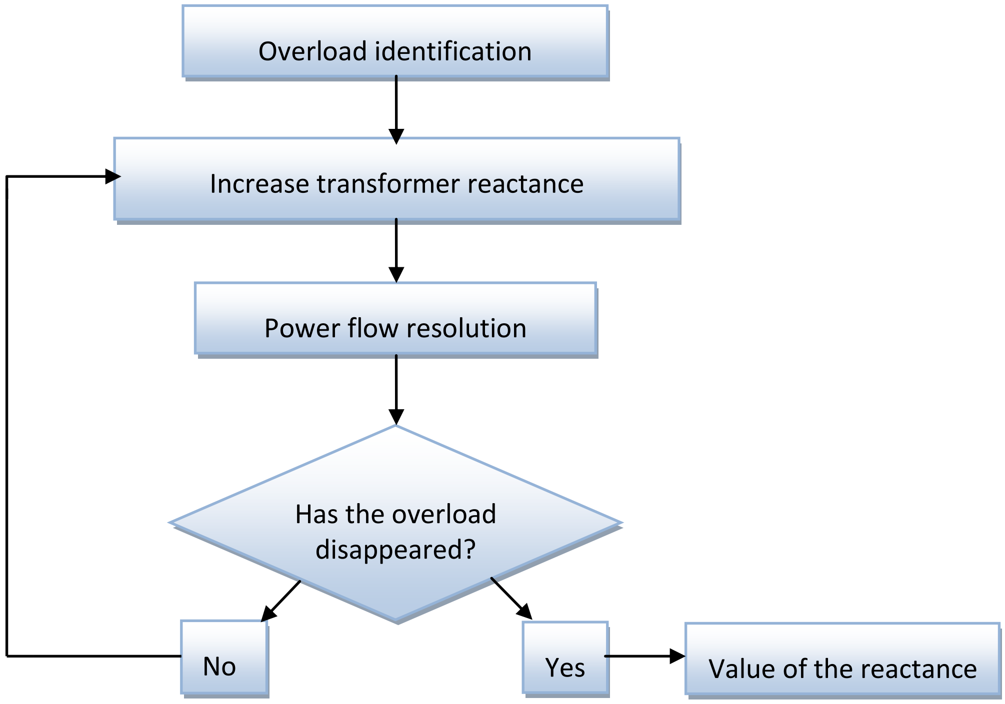


Figure 10: Routine to obtain the value of the FACTS reactance.

The way to perform this routine is as follows: First, once it has identified the value of the overload that exists in transformers substation in Pinar del Rey, it is proceeded to increase the reactance of the transformers.

The reactance of each of the transformers of 600 MVA is 0.01833 pu. (1.48 Ω, from the side of 220 kV), the reactance is increased by 0.005 pu. (this simulates the effect of the OLC, which increases reactance between the two nodes). With this increase, it becomes to solve the power flow with the PSSE/E® program and it is checked if the overloads in transformers have disappeared. If the overload has been removed, the value of reactance that must be added to transformers is obtained, if they not removed begins again to increase the transformer reactance other 0.005 pu until the overload removes.

After the procedure, the reactance values are obtained, they are in results section.

Next, an operation example on FACTS is provided. Initial scenarios consist of a large penetration of electricity from Morocco and high electrical demand in the south of Spain, the figure below; taken from the PSS/E® program reflects the charge level of the two transformers:

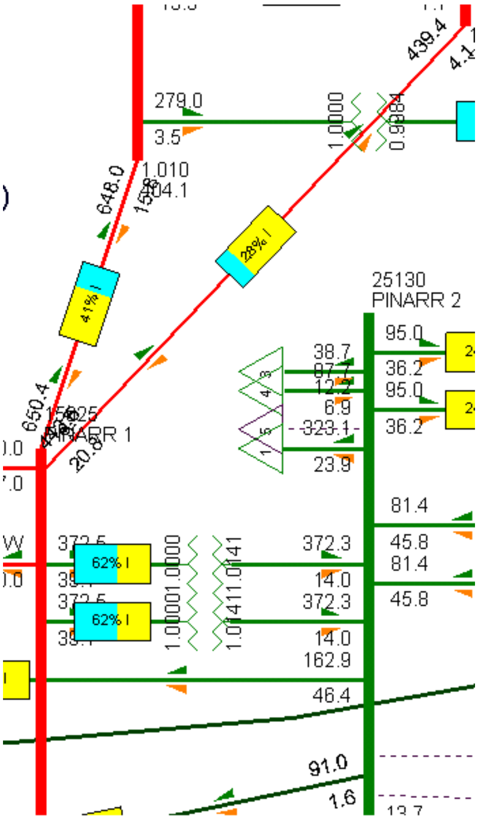


Figure 11: Charge level (62%) of the transformer substation in Pinar del Rey.

In principle, the charge level of transformer is normal (62%), however, and according to the operating criteria of the Spanish system operator (REE PO 1.2, 1998) should be considered security conditions, even under N-1, or as in this case, with the simultaneous loss of both circuits of double circuit lines which share pylons.

Consequently, and after making such contingency analysis, it is found that after the loss of lines Pinar del Rey - Jordana (41%) and Pinar del Rey – Tajo de la Encantada (29%), overloads occur in transformer substation:

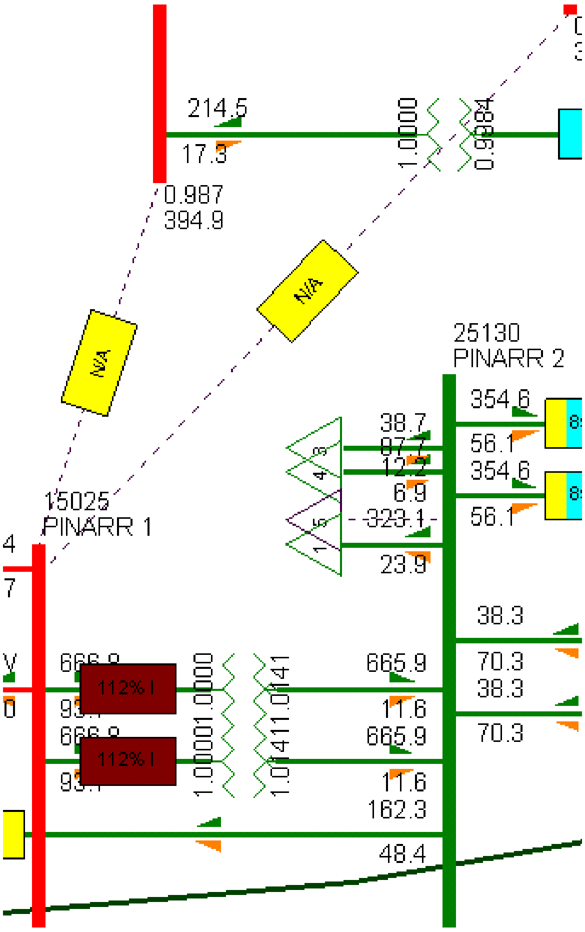


Figure 12: Overload (112%) in transformers substation in Pinar del Rey.

In this situation, the FACTS device (OLC) detects that the active power flow in transformers is higher than the nominal, then acts introducing reactance steps necessary to eliminate this surge, leaving both transformers below its rated power:

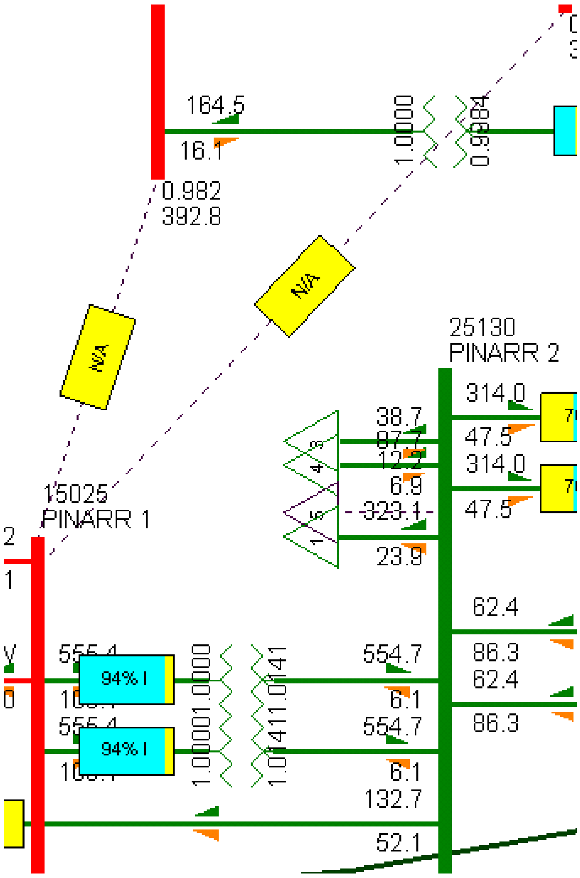


Figure 13: Relief overloads on transformers by introducing steps reactance FACTS device.

Next, an example, where the charge level of transformers is observed, is shown, and how it decreases as the FACTS device adds reactance. In this scenario, the flow through the interconnection is 600 MW from Morocco to Spain and demand in southern Spain is 6.500 MW.

Transformers charge (MVA)	Overload (%)	FACTS reactance (Ω)
672	112	-
630	105	0,2
600	100	0,4
576	96	0,6
540	90	0,8

Table 10: Example of removing overloads through the FACTS performance.

The control system of the OLC has two operation modes (Sánchez, Juan Carlos et al, 2011):

- Closed loop:
  - The OLC device constantly measures the active power flow and acts as the active power level is above the allowable charge levels. For these maximum levels are not exceeded, the OLC introduces the required reactance step.
  - The TSO determines the amount of active power to be flowing through the transformers, consequently the OLC selected reactance steps necessary to achieve it.
- Open loop:
  - The OLC is capable of providing a reactance value equal to that provided by the system operator.

These two modes allow increasing the security of the Spanish electricity system. On one side, the FACTS device lets controlling the surges that may occur and act in real time, and on the other hand serves as a support and control to the system operator to redirect power flows even in the absence overloads.

Furthermore, OLC device serves as a support before maintenance situations. If, for example, maintenance operations should be performed in either the substation transformer, it would be sufficient disconnecting the transformer to maintain, leaving only the second transformer connected in series with the FACTS. If at any time it is exceed the power rating of the transformer, the FACTS will act redirecting power flows. Thus, the OLC provides greater flexibility to the electrical system, ensuring continuity of supply.

3.7 RESULTS

After carrying out the study of power flow of the southern Spanish transmission network, it has been obtained the following results:

- The best location for the FACTS device is the Pinar del Rey substation in Cádiz, this substation transform the voltage from 400 kV to 220 kV.
- There are four different scenarios, depending on the south demand in which are observed overloads in substation’s transformers:

South demand (MW)	Transformer load level (MVA)	Load level (%)
6.000	624	104
6.250	648	108
6.500	672	112
6.750	690	115

Table 11: Overloaded transformers to different levels of electrical demand.

- The reactance values are listed in the next table. Thanks to the different combinations that can be obtained using the switches, the OLC provides in this case 7 different reactance steps to eliminate overloads may occur

Reactance number	Value (Ω)
1	0,2
2	0,4
3	0,6

Table 12: Reactance values for the OLC device.

3.8 CONCLUSIONS

This change in flow through the interconnection can cause overloads in the Spanish electricity system, especially when the electricity demand in the south is high (above 6.000 MW). The weakest point south transmission system is the substation of Pinar del Rey (Cádiz). Such overloads can lead to failure of the transformer substation, so the continuity of electricity supply may be in danger.

In this situation, the installation of a FACTS device (OLC) in series with the two substation transformers will allow real-time control and elimination of overloads, giving more power capacity and flexibility to the power system. Simultaneously, the FACTS device serves as a support and control to the system operator, even when there are no overloads.

Chapter 4 FACTS DESIGN

4.1 INTRODUCTION

In this section, it will be described the technical specifications of the OLC device. The technical specification will allow determining the additional equipment for the proper functioning of the device. Moreover, in order to determine the insulation level of all the equipment and the dynamic response of those, it has been necessary study the transmission network and the technical characteristics of the substation.

4.2 TECHNICAL SPECIFICATIONS OF OLC

The total OLC reactance is 1,2 ohms, nominal current value is 3.150 A, and the three-phase reactive power output of the device is rated 36 MVA, calculated as:

$$Q = 3 \cdot X \cdot I^2$$

Equation 4: Three-phase reactive power of OLC device.

Where Q is the three-phase reactive power, X is the total reactance and I is the rated current.

The FACTS will be installed between the bus bars of the 220kV substation and transformers. Then a basic outline about OLC installation is shown with respect to the transformers (T1 and T2):

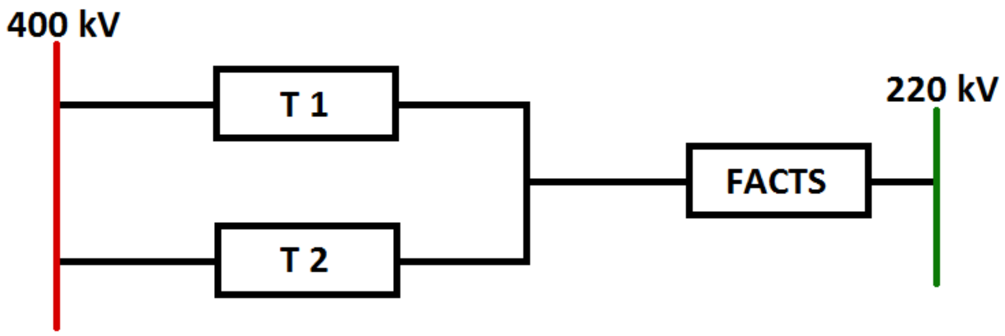


Figure 14: FACTS installation between transformers and 220 kV bus bars.

4.3 NETWORK CHARACTERISTIC

To determine the characteristics of the machine, it must make a preliminary study of the network which specifies the rated values and the network configuration.

1) Voltage and frequency.
   - The nominal voltage (phase to phase) is 220 kV.
   - Maximum continuous voltage is 245 kV.
   - The temporary surge will be according to UNE EN 60071-1. Insulation coordination for equipment isolation levels listed in rank 1 (1 kV ≤ Um ≤ 245 kV). Highest voltage for equipment (r.m.s. value in kV) of 245 kV. Standard short-duration power-frequency withstand voltage (r.m.s value in kV) of 460 kV. Standard lighting impulse withstand voltage (peak value in kV) of 1050 kV.
   - Nominal frequency of 50 Hz. Maximum and minimum values allowed continuous frequency: 50.15 Hz and 49.85 Hz, respectively.
   - Values of maximum and minimum frequency for 300 s: 50.25 Hz and 49.75 Hz

2) Required insulation levels, creepage distance and substation clearances.
   - Minimum lightning impulse withstand level: 1050 kV.
   - Minimum switching impulse withstand level wet: 850 kV.
   - Rated surge arrester voltage: 198 kV.
   - Maximum power-frequency withstand voltage 1 min. dry or 10 sec. wet: 460 kV.
   - Minimum unified specific creepage distance, phase-ground: 54 mm/kV.
   - Minimum phase-ground clearance: 2100 mm.
   - Minimum phase to phase clearance: 2100 mm.
   - Minimum height of live conductor above ground in area accessible with plant energized: 6000 mm.
3) Transmission system grounding.
   The side of the 220 kV transmission system in the Pinar del Rey substation is solidly grounded.
4) Transmission capacity.
   Each transformer substation Pinar del Rey has a rated capacity of 600 MVA, so the transmission capacity will be 1.200 MVA.

With these features, and it would be possible to determine the required BIL rating for the reactances and the values that the FACTS device can be subjected in operation. However, it will do a more detailed analysis of the necessary equipment and systems that accompany the installation of FACTS.

4.4 MAIN EQUIPMENT

Next, there is an aerial view of the substation Pinar del Rey, where the FACTS device will be installed:

Figure 15: Aerial view of the substation Pinar del Rey (Cádiz).

In order to install the FACTS device next to the transformers, there are some necessary additional equipment to ensure the properly operation of the OLC.

1) Reactance:
   For each reactance step the reactive output rating is specified:

Rated reactance	0,2 Ω/phase
Rated current	3.150 A/phase
Rated reactive power	5,9 MVAr/3-phase

Table 13: Characteristic of reactance number 1.

Rated reactance	0,4 Ω/phase
Rated current	3.150 A/phase
Rated reactive power	11,9 MVAr/3-phase

Table 14: Characteristic of reactance number 2.

Rated reactance	0,6 Ω/phase
Rated current	3.150 A/phase
Rated reactive power	5,9 MVAr/3-phase

Table 15: Characteristic of reactance number 3.

The reactance tolerance between phases is ±2%, and the reactance tolerance of each phase is 0/+10%. (IEC 60076-6, 2007).

2) Circuit breaker:
This element will be connected in parallel with each reactance step and the overvoltage protection equipment. Its duty is not to clear system faults, which corresponds to the line circuit breaker, however it must withstands the minimum requirements from the networks characteristic related to overvoltages during power-frequency operation, switching maneuvers and lightening phenomenon.

Maximum continuous voltage	245 kV.
Rated current	4.000 A.
Rated short-circuit current	40 kA.
Power frequency withstand voltage	460 kV.
Lightning impulse withstand voltage	1050 kV.

Table 16: Characteristic of the circuit breaker.

With these data, a circuit breaker is selected from ABB® catalogue (ABB Circuit Breaker, 2014). The circuit breaker corresponds to LTB245E1, 245 kV.

3) Metal-oxide varistors (MOV)
The main duty of this element is to protect the OLC reactances against the overvoltages may appear in the transmission system, as a consequence of switching or lightning phenomena. It is installed in parallel with the circuit breaker and the reactance.
The MOV installed has to be capable of withstanding a minimum lightning value of 850 kV and a power frequency value of 360 kV. So, in order to install a metal-

oxide varistor, it will include information about type, configuration, short-time energy rating, U/I curve, so on (IEC 60099-4).

4) Circuit breaker (by-pass switch)

All the elements next have air insulation in 220 kV.

4.1) Breaker: singlepole control with cut chamber in SF6, and next characteristics:

Highest voltage: 245 kV.
Nominal current: 3.150 A.
Symmetrical cut current: 40 kA.

The circuit breaker selected is LTB245E1, 245 kV (ABB Circuit Breaker, 2014).

4.2) Current transformer:

Highest voltage: 245 kV.
Thermal current limit (1s): 40 kA.

The current transformer selected is IMB 245, rated current 2000 A (ABB Current Transformer, 2012).

4.3) Busbar disconnector: rotating type with monitoring three-pole control:

Highest voltage: 245 kV.
Nominal current: 3.150 A.
Thermal current limit: 40 kA.

4.4) Disconnector isolation: rotating type with monitoring three-pole control:

Highest voltage: 245 kV.
Nominal current: 3.150 A.
Thermal current limit: 40 kA.

The disconnector isolation selected is a horizontal center break disconnector type GW55, 245 kV (ABB Horizontal center break, 2013).

4.5) Grounding disconnector: Monitoring three-pole control:

Highest voltage: 245 kV.
Nominal current: 3.150 A.
Thermal current limit: 40 kA.

4.6) Lighting arrester:

Nominal voltage: 192 kV.
Continual operation voltage: 158 kV.
Nominal current of discharge: 10 kA.

The lighting arrester selected is TEXLIM P-A, maximum system voltage of 245 kV, rated voltage of 192 kV and current of discharge of 10 kA (ABB Lighting Arrester, 2014).

5) Communication system:

In order to establish the communication between the OLC system and other communications equipments installed in the substation, it is necessary to install a communication system. Moreover, this communication system allows the substation control unit communicates with the OLC system.

4.5 RESULTS

The following table resumes the technical specifications of the OLC device

Total reactance	1,2 Ω.
Number of steps	3
Reactance per step	0,2 Ω. – 0,4 Ω. – 0,6 Ω.
Nominal current	3.150 A.
Three-phase reactive power	36 MVA.

Table 17: Technical specifications of the OLC device

Because there is no public information available on the actual cost of OLC device, equipment cost has been estimated based on the cost of similar technologies and reports on the economic impact of FACTS devices (García-González, Javier et al, 2013). It was considered, therefore, that the cost of investment in the FACTS device is 50 € /kVar. Therefore the cost of OLC device will be 1.800.000 €.

4.6 CONCLUSIONS

It is necessary to determine the technical characteristics that the FACTS device has to have, such as the reactance value, the reactive power, so on. These characteristics will allow the proper functioning of the device in order to relive the possible contingences may occur.

In order to ensure the proper functioning of the device, and determine that the introduction of this device do not put in risk the stability of the system, or the OLC is not damaged, the OLC is installed with other equipment such as metal-oxide varistors, circuit breakers that protect it.

Finally, the total cost of the equipment has been estimated at 1.800.000 €.

Chapter 5 ECONOMIC ANALYSIS

5.1 INTRODUCTION

In this section, it will proceed with an economic analysis that justifies the investment in the FACTS device. Potential benefits of the installation of FACTS and an analysis of the amortization of the equipment are explained.

5.2 METHODOLOGY

The installation of the FACTS device avoids the redispatches and the associated cost thereof. A redispatch consist on reducing the conventional generation in order to relieve the overloads may appear in the transmission network.

In order to model this, the previous scenarios created in PSS/E® are used again; the way to perform this is the next: Each scenario which contains overloads is studied, the possible unit generators that can be reduced are selected, and it is reduced the power of these units, it is observed how the overload is eliminated.

The cost of redispatch is calculated as the necessary power to eliminate the overload, multiplied by the redispatch price. This price is calculated as the difference between the cost of unit that enters in the generation scheme and the marginal market price.

5.3 BENEFITS OF FACTS

To avoid overloading in the power transmission system, the Spanish system operator checks hourly technical constraints that may occur once the electricity market is closed the previous day. If inside the technical constraints check, the generation scheme does not meet the safety requirements or overloads are detected, the system operator would implement the following measures (REE PO 3.2, 2013):

- First, the system operator would perform topological operations (switches, bus bar substations connecting, etc...).
- If the overload remains, the system operator redispatches conventional generation in the congested area.
- If the above measures have not been effective or cannot be applied, it is proceed to curtail wind power.

The cheapest solution appears to be trying to eliminate overloads by maneuvers topological system; however these measures can be put in a commitment to the security of the system and increase future maintenance costs. The redispatch is the measure entails a greater impact on operating costs, while cutting wind is always the last measure taken to relieve overloads.

If overload in a certain area are not uncommon, the system operator must resort to investments resulting strengthening in the transmission network (e.g. building new line or increase power transformers). This type of system improvements require large investments and construction times quite high, also encountering strong opposition from the public opinion, mainly due to environmental factors. In this project, the reinforcement of the network would consist of the installation of two power transformers of 1000 MVA.

The FACTS device can be considered a medium-term solution to eliminate surges, providing three different beneficial aspects for the system:

- Conventional generation redispatch is avoided: The redispatch has an associated additional cost to the system, which corresponds to the difference between the cost of energy generated by the redispatched unit and the cost of energy generated marginal cost (electricity market prices from the previous day). This is the most important cost in evaluating the economic impact of the installation of FACTS.
- Introduction of large amount of electricity from Morocco safely: If the OLC device is not installed would not be possible to fit the high volume of energy from Morocco, being necessary to support that electricity through power plants in the Spanish electricity system. Consequently, the OLC mean a fossil fuel saving (to provide some of that energy would be necessary to turn on combined cycle or coal power plants) as well as avoiding the emission of greenhouse gases and CO_2 to the atmosphere, since most of energy would be imported from Morocco will come from renewable sources.
- The FACTS defers investments: The Increased capacity and flexibility that FACTS provides, can defer the investments needed to alleviate the continuous overloads in transmission network. The economic benefit of postponing investment has to do with the time value of money.

5.4 REDISPATCHES

If an overload is detected in an area, the transmission system operator can perform a redispatch for relieving this overload. The aim is to relieve the overload in the area, reducing the generation in the area. Because at all times it must be maintained a constant balance between generation and demand, if the generation is reduced in an area, diminished power that must be offset by some other generator into the electrical system without affecting relieved before overload. As this unit enters to meet the diminished had not previously entered in the electric power market, has an associated cost exceeds marginal cost of electricity market.

As redispatches suppose the greatest economic impact on the operating costs of the system, it will proceed with an analysis that quantifies the cost thereof. This is going back to work on the stage of the PSS/E® program which overloads found.

When overloads are obtained in a given scenario, the first step is to analyze the sensitivity of each of the generators that can be redispatched. It is considered that an overload disappears when the charge level transformers in Pinar del Rey is below 95%.

In this case, in the south of the Spanish electricity transmission system network, there are 4 possible generating units to redispatch; the following table lists each of the generators:

Name	Type	Installed power (MW)
Arcos de la frontera	Combined cycle	1.619
Algeciras	Gas natural thermal power plant	821
Barrios	Coal thermal power plant	589
Gibraltar	Combined cycle	781

Table 18: Conventional generators in the South likely to be redispatched.

After analyzing the sensitivity of each of the generators and seeing how the overloads respond to the power down these plants, the following conclusions are obtained:

- First, the Algeciras power plant cannot be redispatched facing overload of transformers in Pinar del Rey. Decreasing the power of this plant, involves increasing overload in transformers. This is because Algeciras power plant is connected to the 220 kV network, and decrease the power supplying network, causes the power flow through the transformers increases in order to supply the power required in the 220 kV side.
- The sensitivity of the Arcos de la frontera generators is less than the generators of Barrios and Gibraltar, this means that to achieve to eliminate overload of transformers, it is required to reduce much more power from Arcos de la frontera generators than of Gibraltar or Barrios.
- The sensitivity of the Barrios power plant is the same as that of Gibraltar, that is, to eliminate overloads of transformers, it is required to reduce the same amount of power.

As mentioned before the redispatch leads to charges associated operating system. With the installation of FACTS, this cost can be avoided because the FACTS rectify the overload instantly without resorting to redispatches.

This additional cost has been calculated as follows:

$$RC_j = \sum_{i=1}^{N} P_i \cdot H_i \cdot (\lambda_r - \lambda_c)_j \ \forall j$$

Equation 5: Redispatch cost.

Where RC_j represents the cost of redispatch in the situation "j" (Peak, plain, valley); P_i is the power to redispatch on stage "i", H_i the number of hours that should redispatch on stage"i", λ_r is the cost of the unit enters to meet the redispatched power and λ_c is the average market marginal price.

For the difference between the cost of redispatched unit and the marginal price of the electricity market has been carried out as follows:

The marginal price of electricity market was obtained for each hour of the year 2013 (ESIOS, 2013), with these data it has obtained a monthly average for each hour of the day, thereby obtaining 24-month average prices for each. For the price of redispatch units have been obtained the weighted average monthly price of Phase I to rise. The difference between the weighted price of Phase I to rise and the average marginal price of electricity market is the total cost of redispatch in that hour (€ / MWh).

As each time has been associated with a label (Valley, plain and Peak), an average cost of redispatch is finally settled as peak, plain or valley:

	Peak	Plain	Valley
Redispatch cost (€/MWh)	115,19	103,83	99,13

Table 19: Redispatch cost schedule according peak, valley or plain tip.

It is noted that the redispatch cost is greater in valley schedule than in peak schedule, this is mainly due to the marginal price of electricity market hours valley is lower than in the peak, making the redispatch cost higher.

The next step is to identify the necessary power to be redispatched to eliminate overloads. It will decrease the power in some cases from the Barrios power plant and in other cases from Gibraltar power station, as the sensitivity is the same, until the charge level of the transformers is 95%. The annexes attached in more detail, a table showing how the overloads are removed progressively as the generation decreases. The following table collected, the power required in general to eliminate overloads for different scenarios:

Scenario	South demand (MW)	Transformers charge (MVA)	Cherge level (%)	Power required to redispatch (MW)
1	6.000	624	104	400
2	6.250	648	108	500
3	6.500	672	112	600
4	6.750	690	115	667,47(*)

Table 20: Power required to redispatch at each scenario.

(*)The power has decreased in Gibraltar power plant, which was at this stage delivering this power (667,47 MW) and simply disconnecting all the generation of this plant, overloads on transformers were reduced.

Finally it is calculated the number of hours that the situations described occur, resorting to section [1], where the profile of the interconnection was analyzed and the number of hours which interconnection limit was reached. Now it adds to the study the number of hours that the electricity demand of the south of Spain is above certain levels, distinguishing if scenarios peak, plain or valley. The following table shows the number of scheduled hours for each stage is:

Peak schedule:

Scenario	Interconnection flow (MW)	South demand (MW)	Number of hours
1	600	6.000	24
2	600	6.250	29
3	600	6.500	37
4	600	6.750	90

Table 21: Number of hours overload scenarios occur in peak hours.

Plain schedule:

Scenario	Interconnection flow (MW)	South demand (MW)	Number of hours
1	600	6.000	74
2	600	6.250	91
3	600	6.500	94
4	600	6.750	127

Table 22: Number of hours overload scneraios occur in plain hours.

Valley schedule:

Scenario	Interconnection flow (MW)	South demand (MW)	Number of hours
1	600	6.000	0
2	600	6.250	0
3	600	6.500	0
4	600	6.750	0

Table 23: Number of hours overload scenarios occur in valley hours.

Then redispatches cost will be, according to equation [5]:

	Redispatch cost – RC_J (€)
Valley	0
Plain	22.456.954,05
Peak	21.439.870,08
Total	43.896.824,13

Table 24: Total cost of redispacthes.

5.5 AMORTIZATION FACTS DEVICE

In this section, the amortization of the FACTS device is calculated, the total investment cost of the FACTS device is 1.800.000 €; the amortization is calculated supposing a lifetime of 20 years and a interest rate of 8%.

The annualized investment cost is calculated as:

$$AIC = \frac{TC}{LRF}$$

Equation 6: Annualized investment cost.

Where AIC is the annualized investment cost, TC is the total cost of the device and LRF, loan repayment factor, which is calculated as:

$$LRF = \frac{1 - \frac{1}{(1+r)^n}}{r}$$

Equation 7: Loan repayment factor.

Where “r” is the interest rate and “n” is the expected lifetime.

The following table shows the annual investment cost of OLC device:

	OLC
Investment cost (€/kVar)	50
Power (MVar)	36
Total cost (€)	1.800.000
Expected lifetime (years)	20
Interest rate (%)	8
Annualized investment cost (€)	183.673,46

Table 25: Investment cost of OLC device.

5.6 RESULTS

After carrying out the economic analysis of the installation of FACTS device, it is obtained the next results:

- The total investment cost of the OLC device is 1.800.000 €, with an annualized investment cost of 183.673,46 €.
- The installation of the OLC device could avoid the redispatches and the associated cost of thereof in scenarios of high penetration of electrical energy from Morocco and high demand in southern Spain. This cost has been estimated at 43.896.824,13 €.

5.7 CONCLUSIONS

For 2020, if Morocco exports large amounts of electrical energy to Spain, the reliability of the southern Spanish transmission system could be in danger, specifically when the south electrical demand is high.

The installation of the OLC device will allow increasing the transmission network safety in this case, and avoiding the redispatches and the associated cost of thereof; thus, the interconnection capacity of Spain is improved without undertaking further measures and deferring future investment.

In this project, it is estimated that in 2020, costs per redispatches only on the considered scenario can be approximately 43.000.000 euros. Therefore FACTS device could reduce the operating costs of the system, since the cost of the device is only 1,8 million euros compared.

Chapter 6 FUTURE DEVELOPMENTS

This project aims to be a small benefit analysis that can provide the installation of FACTS devices for power system operation.

The objectives of this project were contemplated in 2020, the year that changes arising in the Moroccan energy policy. However it would be interesting to study the same goals but for the period 2030-2050, which is expected to reach maturity MEDGRID project and the establishment of other projects such as DESERTEC, which aims to install large amounts of renewable energy especially in the Sahara desert to meet much of the global electricity demand (DESERTEC, 2009). Both large projects, try to interconnect European electricity systems in North Africa by electrical interconnections in the Mediterranean, to create what is known as a supergrid. Therefore the study of the impact of these interconnections can be associated with the installation of FACTS devices that allow for flexibility to European electrical systems.

Currently, there are a relatively large variety of FACTS devices. Parallel FACTS, as Static Var Compensator (SVC), FACTS series as Thyristor Switched Series Capacitor (TSSC) or combined FACTS like Dynamic Flow Controller (DFC) for controlling other electrical parameters of the transport system, as voltage, current, reactive power or the short circuit current. Then the application of FACTS can also be considered from another perspective as security features to improve the quality and continuity of electricity supply, controlling other parameters.

In addition, it could implement the installation of FACTS devices to other scenarios where their use is practical and beneficial to the electrical system. This applies, for example, scenarios with high penetration of wind energy, due to the difficulty of prediction, can cause overloading of the electrical elements transport system that can be solved in real time by the actions of some kind of FACTS.

Finally, a great use of FACTS devices would be installed in the distribution network, which is spreading and is known as DFACTS (FACTS applied to distribution networks). Distribution networks are usually radial networks operating, shortly meshed and have very low levels of control and monitoring. Thus, the application of DFACTS, will improve control and security of electricity supply, while implies a small improvement in monitoring and real-time control of such networks. It will be important to install this type of equipment for the future development of smart grids in agreement with distributed generation.

Chapter 7 REFERENCES

(ABB Circuit Breaker, 2014) ABB, *Buyers's guide HV Live Tank Circuit Breakers,* 2014.

(ABB Current Transformer, 2012) ABB, *Oil Insulated Outdoor Instrument Transformers Buyer's Guide*, 2012.

(ABB Horizontal center break, 2013) ABB, *Horizontal center break disconnector type GW55, up to 245 kV*, 2013.

(ABB Lighting Arrester, 2014) ABB, *High Voltage Surge Arresters Buyer's Guide – Section TEXLIM P-A*, 2014.

(Branche Electricité - Bilan des Activités, 2012) ONEE, *Branche Electricité - Bilan des Activités industrielles et commerciales*, 2012.

(DESERTEC, 2009) DESERTEC Foundation, *The DESERTEC Concept*, 2009.

(ENTSO-E, 2013) ENTO-E, *Scenario Outlook and adequacy forecast 2013-2030*, 2013.

(ESIOS, 2010) ESIOS Red Eléctrica de España, *Programa diario base de funcionamiento*, 2010.

(ESIOS, 2013) ESIOS Red Eléctrica de España, *Precios marginales mercado diario*, 2013.

(García-González, Javier et al, 2013) Javier García-González et al, *Economic impact analysis of the demonstrations in task-forces TF1 and TF3*, TWENTIES 2014.

(ICEX, 2010) ICEX, *El sector de la energía solar y otras energías renovables en Marruecos*, 2010.

(ICEX, 2012) ICEX, *El sector de las energías renovables en Marruecos*, 2012.

(IEC 60076-6, 2007) International Electrotechnical Commission, *Power transformers – Part 6: Reactors.* 2007.

(IEC 60099-4, 2004) International Electrotechnical Commission, *Surge arresters – Part 4: Metal-oxide surge arresters without gaps, 2004.*

(Le Maroc, pays des energies renouvelabes, 2012) ONEE, *Le Maro, pays de energies renouvelables*, 2010.

(MEDGRID, 2010) MEDGRID, *Brochure – Opening*, 2010.

(REE P.O 1.2, 1998) Red Eléctrica de España, *Procedimientos de operación: 1.2 Niveles admisibles carga red*, 1998.

(REE P.O 3.2, 2013) Red Eléctrica de España, *Procedimientos de operación: 3.2 Resolución de restricciones técnicas*, 2013.

(REE, 2013) Red Eléctrica de España, *Avance del sistema eléctrico español 2013*, 2013.

(Sánchez, Juan Carlos et al, 2011) Sánchez, Juan Carlos et al, *OLC Conceptual Design and Equipment Specification*, ABB, REE, TWENTIES, 2011.

Chapter 8 ANNEX

Overloads from the different PSS/E® scenarios and facts action:

Scenario	South demand (MW)	South generation (MW)	Transformers charge (MVA)	Charge level (%)	Transformer reactance (pu)	Facts reactance (pu)
1	6.000	6.426	624	104	0,001833	-
1	6.000	6.426	600	100	0,02333	0,005
1	6.000	6.426	558	93	0,02833	0,01
2	6.250	6.676	648	108	0,01833	-
2	6.250	6.676	612	102	0,02333	0,005
2	6.250	6.676	576	96	0,02833	0,01
2	6.250	6.676	552	92	0,03333	0,015
3	6.500	6.926	672	112	0,01833	-
3	6.500	6.926	630	105	0,02333	0,005
3	6.500	6.926	600	100	0,02833	0,01
3	6.500	6.926	576	96	0,03333	0,015
3	6.500	6.926	540	90	0,03833	0,02

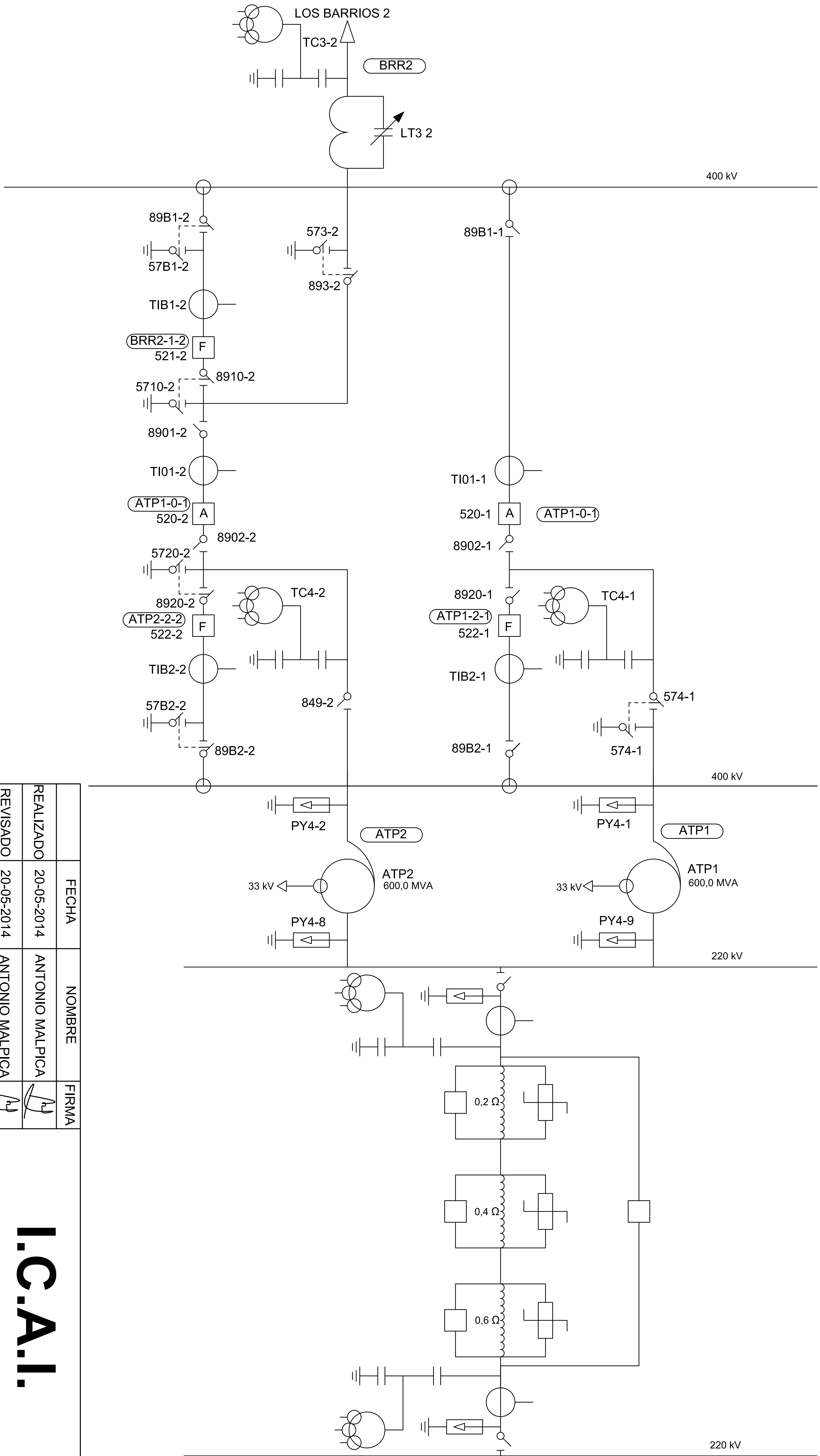
4	6.750	7.176	690	115	0,01833	-
4	6.750	7.176	654	109	0,02333	0,005
4	6.750	7.176	618	103	0,02833	0,01
4	6.750	7.176	588	98	0,03333	0,015
4	6.750	7.176	558	93	0,03833	0,02

Redispatches from the different PSS/E® scenarios:

Scenario	Demand	Generation	Arcos de la Frontera (MW)					Algeciras (MW)		Barrios (MW)	Gibraltar (MW)	Transformer charge level (%)	Total rredispatch (MW)
			ArcosF52	ArcosF53	ArcosF51	ArcosF4	ArcosF3	Algec3	Algec4				
1	6.000	6.426	168,24	168,24	168,24	439,8	193,34	298,98	216,35	602,52	597,71	104	
1										502,52		101	
1										402,52		98	
1										352,52		97	
1										302,52		95	
1										202,52		92	400
1	6.000	6.426	168,24	168,24	168,24	439,8	193,34	298,98	216,35	602,52	597,71	104	
1											497,71	101	
1											397,71	98	
1											297,71	96	
1											197,71	92	400

1	6.000	6.426	168,24	168,24	168,24	439,80	193,34	298,98	216,36	602,53	597,71	104	
1								249,98	166,36			108	100
1	6.000	6.426	168,24	168,24	168,24	439,80	193,34	298,98	216,36	602,53	597,71	104	
1			148,24	148,24	148,24	419,80	173,34					102	
1			128,24	128,24	128,24	399,80	153,34					100	
1			88,24	88,24	88,24	359,80	113,34					97	
1			48,24	48,24	48,24	319,80	73,34					93	537
2	6.250	6.676	174,79	174,79	174,79	456,91	200,87	310,62	224,78	625,97	620,97	108	
2										525,97		105	
2										225,97		96	
2										125,97		93	500
2	6250	6676	174,78	174,78	174,78	456,91	200,86	310,61	224,77	625,96	620,96	108	
2											220,96	96	
2											120,96	93	500

3	6.500	6.926	181,33	181,33	181,33	474,02	208,38	322,25	233,19	649,41	644,22	112	
3										249,41		99	
3										149,41		96	
3										49,41		93	600
4	6.750	7.176	187,88	187,88	187,88	491,13	215,91	333,88	241,61	672,85	667,48	115	
4										372,85		106	
4										272,85		103	
4										172,85		100	
4										72,85		97	
4										0,00		95	672,85
4	6.750	7.176	187,88	187,88	187,88	491,13	215,91	333,88	241,61	672,85	667,48	115,00	
4											67,48	97,00	
4											0,00	95,00	667,48



S/E
ESCALA:
REVISADO 20-05-2014 ANTONIO MALPICA
REALIZADO 20-05-2014 ANTONIO MALPICA
FECHA
NOMBRE
FIRMA
SITUACIÓN
I.C.A.I.
PLANO Nº.
1