Automatic load shedding scheme and the integration of new capacitors’ controller in the South-West region of France to mitigate large scale voltage collapses

Geoffrey Senac

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Geoffrey SENAC

Supervisor at RTE
Hervé LEFEBVRE

Supervisors at KTH
Lennart SÖDER
Ruijioj LEELARUJI
Abstract

Since the modern world is totally dependent on electricity, it is necessary to ensure that electrical power is generated and transmitted to end users with minimum interruptions. Given the importance of electricity for the operation of our society, it is really important to fill continuously good safety conditions. This policy must handle two major areas: reducing the risk of occurrence of a crisis and its management if a very constraining disturbance happens. This master’s thesis is mainly focused on this last point.

With the continuous increasing of consumption and the high investment costs, it becomes more complicated to ensure good safety margins, since the network is exploited closer to its limits. A recent study demonstrates that the South-West region of France was prone to voltage collapses after very severe faults and as a result the need of an under-voltage load shedding in this region was evoked.

In parallel, to ensure the voltage stability, RTE (Réseau de Transport d’Electricité - Electricity Transmission Network) has invested also in equipments such as capacitors and static reactive power compensators. With newly installation of compensation means on the network, the necessity to develop a new device called SMACC (Système avancé pour le contrôle de la compensation - Advanced system for the control of the compensation) capable of handling more efficiently the control of these batteries of capacitors has been highlighted.

Ultimately the thesis focuses also on the new HVDC (High-voltage direct current) line between France and Spain. This line is a key for long-term voltage stability study, since it increases the exchange capacity between France and Spain, and has the ability to provide or absorb reactive power to the network.
I would like to express my very great appreciation to my supervisor Hervé LEFEBVRE for his welcome, patience guidance and continuous advice and for everything he taught me during this master’s thesis regarding the system’s operation and more particularly the voltage stability issues.

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Last but not least, I would like to dedicate this master’s thesis to my parents and to my girlfriend Anissa. To my parents for the education, support and encouragement they provided me over the years. They gave me much more that I could except, and without them I may never have been the person I am today. To my girlfriend for her constant love, her patience and support all along my studies even in the most difficult times.

Finally I cannot conclude without having a huge thought to my brother and I wish him all the best for the rest of his studies.
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Abbreviations

**ACMC** Automate pour le contrôle des moyens de compensations - Automaton for the control of compensation means

**EHV** Extra-high voltage

**HV** High voltage

**HVDC** High-voltage direct current

**LSD** Load shedding device

**OLTC** On-load tap changer

**SMACC** Système avancé pour le contrôle de la compensation - Advanced system for the control of the compensation

**SVC** Secondary voltage control

**RTE** Réseau de transport d’électricité - French transmission network

**TSO** Transmission system operator

**UVLS** Under-voltage load shedding
Chapter 1

Company

1.1 Presentation of RTE

1.1.1 Historical background

The history of transmission lines in France dates from the 19th century [1]. This period has seen the arrival of the first private power producers, supplying electricity to people from their own power plants through their own transmission system. Thanks to the state involvement in 1929, the first interconnections between different regions were built and in 1938 and all municipalities had an access to electricity.

The World War II contributed also to the transmission lines development. As of 1945, France had the biggest high voltage network of the world with more than 12000 km of lines. At the end of war, a law was voted in order to nationalize 1450 electricity (and gas) generation, transmission and distribution companies and on April 8, 1946, the national entity Electricity de France (EDF) was created.

The end of the century has witnessed the opening of the European market and as a consequence, France had to liberalize its electricity market by separating generation and transmission activities. This separation marks the creation of a new division within EDF in July 2000: Réseau de Transport d’Electricité (RTE).

Finally, the legal separation between RTE and EDF was strengthened in 2005 [2] and RTE became a limited liability subsidiary of EDF whose activities are overseen by the “Commission de régulation de l’Energie” (CRE - Commission for Energy Regulation).

1.1.2 RTE group - public service missions

RTE is the electricity transmission system operator of France and so has to operate, maintain and develop the High Voltage (HV) and Extra High Voltage (EHV) transmission system. RTE assumes a central role between producers (electricity generating units), distribution and also industrial consumers.
In France, ERDF (Electricité Réseau Distribution France), a subsidiary of EDF since 2008, is the main responsible of the distribution of electricity (DSO: Distribution System Operator) on 95% of the French territory. There are also around 160 other DSOs which ensure the electricity distribution in the rest of the country. The figure 1.1 gathers the role of the different actors of the electrical system.

**Figure 1.1: Electrical System**

RTE is committed to the state and therefore is tasked with different responsibilities [3]:

- Balancing production/demand
- Guaranteeing a high-level public service to customers
- Managing network infrastructures
- Contributing to the smooth running of the electricity market

At every moment RTE must handle the electricty flows, by balancing supply and demand which means that the production must be constantly adjusted to the consumption by varying plants output power. RTE has also to guarantee the security of the transmission system has the duty to extend the network and bring the necessary investments to make the system more secure and adaptive to the evolution of external factors such as the consumption, environment, ecology. It has to guarantee at minimal cost an equitable access to all players (industrial consumers and producers) as well as a transparent treatment.

### 1.1.3 Key figures

RTE’s network operates at HV (from 63 to 150 kV) and EHV (225 and 400 kV). It owns the largest transmission system in Europe with more than 104 000 km of lines (both overhead lines
and underground cables). The proportion of EHV lines represents around 46% of the whole network. More than 2700 substations are spread over the territory whose 700 in EHV [4].

Regarding RTE’s customers, there are 700 electricity production units, ERDF which represents 2400 supplying points and finally around 600 industrial sites directly connected to the network. The net generation injected on the network is around 500 TWh a year and is mainly produced by nuclear units (400 TWh). France is also a net exporter of electricity, as shown in figure 1.2, with 46 cross border power lines and a total annual export of 74 TWh[5].

![Cross-border contractual exchanges in 2012](image)

**Figure 1.2: Cross border contractual exchanges in 2012**

### 1.2 The company organization

#### 1.2.1 On the French territory

RTE relies on 8 400 employees whose capacities and activities are categorized into two main parts:

- The power system in charge of electricity flow management
• The transmission network responsible for network maintenance and network development engineering

RTE is organized into seven geographical regions, as illustrated in figure 1.3. The power system is operated by seven regional network control centers (called dispatching) located in each of these regional areas and a centralized center called CNES (National system for System Operation) located in Paris.

![Figure 1.3: Regional dispatching centers](image)

The CNES is the entity responsible for keeping the balance between production and consumption, maintaining voltages levels and loads on the 400 kV network, and managing cross-border electricity flows between France and its neighboring countries. In support of the CNES, the regional centers take care of monitoring and managing voltage levels and load flows on the EHV (225 and 400 kV) and High Voltage (63, 90 and 150 kV) network, as well as telecontrol of high-voltage substations. The power system units enable an access to the network for customers and development of the regional network. In case of disturbances, the control centers have to provide back up for the CNES in order to implement countermeasures to maintain the network integrity.

1.2.2 Expertise and system department

I did my master’s thesis in the Expertise & System Department (called DES) in Versailles which belongs to the R&D unit of RTE. The different divisions of this department, held by around 80 people, are working on different issues related for example to the integration of renewable energies or new technologies, the development of the network infrastructure in the upcoming years as well as the development of software and tools. The competences of the department
cover both the technical field as well as the regulatory and economic aspects. For my part, I was a member of the group GPM (Provisional Handling and Maintenance - Gestion Prévisionnelle et Maintenance) which is mainly focused on voltage stability studies.
Chapter 2

Mission

2.1 Current and upcoming challenges

2.1.1 Supply-demand balance

Transmission System Operators face different challenges. The first one is the continuous increasing of the consumption and more particularly the consumption peak (which was hitting record on February 2012 [6]). The consequences of this trend are for example to make lines and power plants reach their physical limits. An explanation of the phenomenon could be the constant increase of households, the development of new products such as computers or telecommunications and finally the growing of electrical heaters. Another factor is the increase of the European countries temperature-sensitivity, which represents the impact of the climate temperature on the electricity demand.

This phenomenon is really disturbing, especially since the investments made on the network, with the building of new overhead lines or the constructions of new plants, is lagging behind the consumption speed. Then it is more difficult to predict the future consumption as the economic growth is slowing down. Therefore the domestic demand forecasts can be only based on the prediction of the GDP (Growth Domestic Product) growth estimates which gives a large panel of scenarios more or less accurate.

Finally, the fact that more than half of the fossil-fired units will be shut down in 2016 [7] as well as the willing of some countries to end the nuclear generation will be a challenge for the TSOs in the upcoming years to keep the balance between generation and consumption. Many advances were made as the development of load-shedding or energy efficiency measures which tend to reduce the consumption on a wide range. Nonetheless, the concern of the supply-demand balance remains one of the big challenges for the future.

2.1.2 Integration of Renewable Energy

Another phenomenon, which appeared at the end of the 19th century, is imposing some changes in the energy production. With the arrival of some issues such as the global warming, it is essential to find a new way to produce energy. The energy regulation which has known an important evolution started in 1997 with the Kyoto Protocol [8] followed by the Copenhagen Accord [9] in 2002. This momentum is now reaching the European Union members which have planned
in 2007 to reduce their gas emissions by 20% compared to 1990, improve by 20% the energy efficiency measures, and finally integrate more than 20% of renewable energy in the mix [10].

However, TSOs have to deal with the challenging issues that come with the integration of renewable energy units. They are usually located away from the main network and the lines strengthening is often necessary. Then, the production intermittency and climate hazard appears as an hurdle to the development of such technologies and highlights the acute challenges to maintain both a reliable and cost effective supply. Despite various progress in meteorological forecasts and the fact that it is now possible to evaluate the next day production, it is very difficult to predict the three days prior production. A consequence of the randomness of wind and solar energy is that it is unclear how to use these units to control the network’s voltages as well as it remains complicated to adjust active or reactive power production. The non-correlation between renewable production and the consumption is also a major. This is particularly the case for solar units, which produce the most energy in summer whereas the consumption is usually low [11].

2.1.3 Electricity market’s development

At the beginning of the century, we were witnessing a new phenomenon known as "the unbundling of electricity grids and electricity production" which allowed an effective competition on supply and generation. This trend, which came with the liberalization of electricity industry, has led to new challenges. In fact, power companies are no longer vertically integrated (generation, distribution and retail services no longer under one business) and TSOs have to facilitate the development of this electricity market [12].

Furthermore to ensure a smooth running of the European market, new constraints appeared such as [12]:

- independant transmission system operators
- account unbundling for generation, transmission and distribution activities
- independant national regulators

In this new context, which enables an easy access to many players such as traders, competing suppliers or consumers, the TSOs have to manage the complexity of this new system. As RTE is responsible for electricity imports and exports, it has the duty to manage the congestion on the cross-border connections. In that way, the European TSOs have seen their network stretched through the different interconnections. However, even if the mesh increasing provides a mutual assistance between countries in case of shortage, this can also induce large-scale voltage collapses in Europe, caused for example by a single disturbance in only one country. This new particularity shows that high transparency and cooperation are now required between TSOs and all the players.
2.2 Master’s thesis objectives

2.2.1 Aim of the project

The first study of this master’s thesis focuses on a new device (called SMACC) that has recently been developed by RTE to control compensations means, due to the installation of various batteries of capacitors in the South-West of France. The SMACC has already been designed by an internal department at RTE but a deep study regarding the presence of potential interactions has never been done yet.

Then it has been demonstrated that the South-West is still sensitive to voltage collapse after very severe disturbance. A second study is consequently carried out to evaluate whether an automatic load shedding is necessary to mitigate large-scale voltage collapses. The installation of the HVDC (High-voltage direct current) line between France and Spain has also a crucial importance for these studies.

2.2.2 Thesis work outline

Before starting test, the SMACC is introduced in order to have a good understanding of the context. Then the SMACC is modelised in the softwares (both Convergence and Eurostag). The support for our simulations is the situation of the 9th of February 2012. It is necessary to have accurate data, especially on the South-West region of France and on the Spanish network, and to calibrate both situations in Convergence and Eurostag. Then the SMACC is tested and finally some improvements are suggested.

Regarding the load shedding device (LSD), the context of the study is given in a first part. Then a situation at horizon 2020 is studied and calibrated. The LSD is modelized and then integrated into the forecasting situation. Finally different studies are conducted regarding voltage stability by simulating different constraining defaults in the South-West region and different setups of LSD are tested in order to avoid a general voltage collapse as efficiently as possible.

2.2.3 Outline

• The first chapter focuses on RTE where the Master’s Thesis has been done. The company mission is presented and key figures are provided. The context of the Thesis is introduced in the second chapter.

• Chapter 3 provides a theoretical background about voltage stability. Some notions are given regarding the network model and the phenomenon of drop of voltage. The concept of voltage collapse is also introduced.

• Chapter 4 describes the software used during the Master’s Thesis.

• The SMACC and the LSD studies have been made respectively in chapter 5 and 6. In each chapter, a presentation of the context is provided and then a part is devoted for simulations and results.
Chapter 3

Theoretical study

3.1 Introduction of power system stability

According to CIGRE-IEEE [13]: "Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

The power system is continuously subjected to various disturbances and it is necessary that TSOs maintain a high reliability of operation and a satisfactory security level, regardless the network conditions. The latest incidents in the world, such as the one in the United States in 1965 [14], shows the difficulty to operate the Power System. Depending on the network topology, the system operating conditions and the form of the disturbance, the Power System can undergo different types of instabilities. This master’s thesis focuses essentially on voltage stability, and more precisely long-term voltage stability.

Voltage stability refers to the ability for a power system to maintain at all buses acceptable equilibrium voltage values after a disturbance. The driving force for voltage instability is usually the loads. In response to a disturbance, power consumed by the loads tends to be restored by the action of motor slip adjustment, distribution voltage regulators, tap-changing transformers, and thermostats. Restored loads increase the stress on the high voltage network by increasing the reactive power consumption and causing further voltage reduction [13]. It can be useful to classify voltage stability into two categories:

- Small disturbance voltage stability which defines the ability for a power system to keep steady voltage after a small perturbation like a load gradual change. Usually, this form of stability can be studied by linearizing the system dynamic equation.

- Large disturbance voltage stability which is concerned with a system’s ability to control voltage after large disturbances such as system faults, loss of generation, or circuit contingencies.

The time frame of interest for voltage stability can vary from a few seconds to tens of minutes. As a result, voltage stability can be a short-term or a long-term phenomenon.
• Short-term voltage stability, mainly involves dynamics of fast acting load components such as induction motors or HVDC converters, particularly to their inverter terminals. The driving force of instability is the tendency of dynamic load to restore consumed power in the time frame of a second after a voltage drop caused by a contingency.

• Long term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. It can be assumed that the system has survived the short-term period following the initial disturbance and the dynamic time scale can reach several minutes.

This master’s thesis focuses on long-term voltage instability. In the next sections is described how a disturbance may lead to a voltage collapse and the different parameters that can contribute to this type of incident are also emphasized.

3.2 Network model and performance

3.2.1 Line model

Regarding different parameters such as the length as well as the transmitted power, the line may be represented by different models. The transmission lines are mainly classified as short, medium or long lines. Short transmission lines (<80 km) have a very simple model since the parameters are lumped and sometimes can be ignored in the analysis while for long transmission lines (>250 km) the parameters are distributed along the line which makes the analysis more complicated. Thus, it is necessary to take into account propagation phenomena which makes the system more complex to solve.

In order to illustrate the problematic of long-term voltage stability, a simple example is considered and represented by a medium line with length between 80 and 250 km (most of the lines). As a three-phase system is considered, it is possible to study only the per-phase equivalent circuit. Its representation is described in figure 3.1.

![Per-phase equivalent circuit](image)

Figure 3.1: Per-phase equivalent circuit

The different parameters of the line are:

**The series resistance** $R$ : which reflects the joule losses.

**The series inductance** $X_L$ : due to the magnetic field inside and outside the conductor
The shunt capacitance $C$ : due to the difference of potential between conductors

The shunt conductance $G$ : which modelizes the corona effect.

Below are given some magnitude examples:

$R : 3\Omega/100km$

$X_l : 30\Omega/100km$

$C : 1.2\mu F/100km$

$G : 1.2nS/100km$

In our case, the shunt conductance is neglected given the medium line model, as shown in figure 3.2. Then, for high transmitted power, the current may reach high values and it is then possible to neglect also the shunt capacitance in favour of the series inductance.

\[ V_1 \rightarrow R_l \rightarrow X_l \rightarrow I \rightarrow V_2 \]

\[ V_1 \rightarrow Z_{ch} \rightarrow V_2 \]

Figure 3.2: Symplified model

For the study, the generator will be considered as a slack bus (with a constant output voltage and without any power limitations). The load is both resistive and inductive. Furthermore, the line is not lossless (the line resistance is taken into account).

\[ I \rightarrow V_1 \rightarrow \theta \rightarrow \phi \rightarrow V_2 \rightarrow \Delta V \]

Figure 3.3: Vector diagram

First of all, we can start by defining the line impedance $Z$ as well as the voltage difference between the sending and receiving end $\Delta V$:
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\[ Z = R_l + jX_l \]  
\[ \Delta V = ZI = V_1 - V_2 \]

Now, let \( P_2 \) and \( Q_2 \) be the active and reactive power loads, respectively. We can introduce in the same way \( \phi \), the phase shift between \( V_2 \) and \( I \).

\[ P_2 = V_2 I \cos \phi \]  
\[ Q_2 = V_2 I \sin \phi \]  
\[ I = \frac{P_2 - jQ_2}{V_2} \]

We can now develop the equation (3.2):

\[ V_1 = V_2 + R_l I + jX_l I \]

\[ \Delta V = ZI = \frac{(R_l + jX_l)(P_2 - jQ_2)}{V_2} \]

\[ = R_l P_2 + X_l Q_2 + j \left( X_l P_2 - R_l Q_2 \right) \]

\[ = \Delta V_r + j \Delta V_x \]

\[ \theta \]

\[ \Delta V \]

\[ \Delta V_r \]

\[ \Delta V_x \]

Figure 3.4: Vector diagram

From this, it can be noticed that the voltage drop is composed of two components:

- \( \Delta V_r \): the radial part
- \( \Delta V_x \): the quadratic part

\[ |V_1|^2 = (V_2 + \Delta V_r)^2 + \Delta V_x^2 \]

\[ \sin \theta = \frac{\Delta V_x}{\sqrt{((V_2 + \Delta V_r)^2 + \Delta V_x^2)}} \ll 1 \]
CHAPTER 3. THEORETICAL STUDY

Then, it is possible to neglect the quadratic part of the equation 3.9, and the voltage drop induced by the line is:

$$\Delta V = R_l P_2 + X_l Q_2 \frac{V_2}{V_2}$$  \hspace{1cm} (3.12)

Now, if we still consider a high transmitted power value, the series resistance can be neglected:

$$\Delta V = R_l P_2 + X_l Q_2 \frac{V_2}{V_2} \approx X_l Q_2 \frac{V_2}{V_2}$$  \hspace{1cm} (3.13)

This results shows us that the drop of voltage is mainly caused by the reactive power consumed by the load. Therefore, in order to keep $V_2$ constant, it is necessary to apply a variable reactive power production at the receiving point.

3.2.2 Maximal transmissible active power

In order to symplify the problem, only the line inductance is considered and the load will be considered as purely resistive.

![Simple line model](image)

Figure 3.5: Simple line model

$$\Delta V = ZI = X_l I$$  \hspace{1cm} (3.14)

Then, we can symplify the expression of the power consumed by the load and find out the expression of $I$, since $\phi$ equals 0 now.

$$P_2 = V_2 I cos\phi = V_2 I$$  \hspace{1cm} (3.15)

$$V_1 = V_2 + R_l I + j X_l I$$  \hspace{1cm} (3.16)

$$|V_1|^2 = |V_2|^2 + |X_l I|^2$$  \hspace{1cm} (3.17)

$$I = \frac{\sqrt{V_1^2 - V_2^2}}{X_l}$$  \hspace{1cm} (3.18)
From (3.15) and (3.18):

\[ P_2 = \frac{V_2}{X_l} \sqrt{V_1^2 - V_2^2} \]  

(3.19)

Now we can plot the curve of \( V_2 \) as a function of \( P_2 \):

From this diagram, we can highlight three remarkable points. The first two points \( V_a \) and \( V_b \) correspond to the two operating points of the line for a given power. It means that for the same transmitted power it is mathematically possible to operate the system at two different voltages. However, the system never operates at the lowest voltage \( V_b \) since the line current is three times higher and so the reactive losses are much higher.
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$V_{2c}$ is another operating point and corresponds to the voltage of maximal power, also known as the critical point. In order to find the value of $V_{2c}$ and $P_{\text{max}}$, it can be useful to express the transmitted power as a function of the power angle $\theta$:

$$P_2 = \frac{V_1 \cdot V_2}{X_l} \sin \theta \quad (3.20)$$

Since,

$$V_2 = V_1 \cos \theta \quad (3.21)$$

We can express the receiving power as below:

$$P_2 = \frac{V_1 \cdot V_1}{X_l} \sin \theta \cos \theta = \frac{V_1^2}{2X_l} \sin 2\theta \quad (3.22)$$

From (3.22), it can be concluded that $P_2$ is maximal when $\theta = \frac{\pi}{4}$:

$$P_{\text{max}} = \frac{V_1^2}{2X_l} \quad (3.23)$$

Where,

$$V_2 = \frac{V_1}{\sqrt{2}} \quad (3.24)$$

This diagram also shows us that when the load exceeds a specific limit, the receiving voltage drops considerably and the receiving power decreases. This confirms the fact that the lower part of the diagram is an unstable operating part of the system. Now if we consider a pure resistive load, we can derive another expression of the receiving voltage as a function of the power:

$$P_2 = \frac{V_2^2}{R} \quad (3.25)$$

The intersection of both curves in figure 3.8 gives a unique operating point. The operating power is lower than the maximal transmittable power and the operating voltage is also lower than the critical point which means that the system is operating in good conditions.

3.2.3 Reactive loss

As mentioned previously, the reactive variation can be divided by two terms:

- The reactive consumption, linked to the line inductance
The reactive supply, due to the shunt capacitance

It then possible to express the total reactive losses as:

$$Q_{losses} = 3X_l I^2 - 3C \omega V_2^2$$

(3.26)

By supposing that the line voltage remains almost constant, the reactive loss is an increasing function of the line current, as represented in figure 3.10.

When the current on the line is very low, the line reactive supply due to the shunt capacitance is higher than the reactive consumption caused by the line inductance. As a consequence, the line is supplying reactive power. When the current increases and so the complete power, the line inductance tends to increase the reactive consumption, therefore the reactive losses

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increase. In case the complexe power equals around 500 MVar, the reactive supply and the reactive consumption of the line are almost the same. The highest the current is (and so the active power) and the highest are the reactive losses. Since the evolution of the losses is proportional to the square of the current, it is then really necessary to distribute the active power flows on a maximum of lines.

3.2.4 Influence of some parameters

Voltage Source $V_1$

The sending voltage has a large influence on both the receiving voltage and on the maximal transmissible power. The expression of the receiving active power is (3.19) as demonstrated in 3.2.2. On the figure 3.11, differents curves have been ploted with different sending voltage value. (For each curve the line inductance has the same value).

It worth noticed that the value of $V_2$ increases with the voltage source $V_1$. Then, we can also notice that a higher sending voltage leads to a higher maximal transmissible power and therefore the power margins are increased for a given load power.

Line reactance $X_l$

We have seen that the drop of voltage and the transmissible power can be respectively expressed by 3.13 and 3.19. Both equations show us that the series inductance value has a huge influence on system reliability. Firstly, the value of the drop of voltage is high if the inductance line is high in the same way. Secondly, the maximal power is lower if the inductance line is higher. The diagram 3.12 represents 3 power curves each with a different value of $X_l$ ($V_1$ is fixed now).
We can notice that the inductance has an opposite effect to $V_1$. For a given load power, the receiving voltage is lower if the inductance is higher. Then, a high value of the inductance induces a low maximal power. We conclude that it is preferable to operate the system with a low value of $X_l$ in order to avoid an important voltage drop.

**Load impedance $Z$**

In order to evaluate the load impedance impact on the system, we cannot consider a purely resistive load anymore. We still consider a perfect generator and a purely inductive line (see figure 3.5). We have already expressed the transmitted power as a function of the power angle in equation (3.20). It then possible to express the transmitted reactive power $Q_2$ as a function of the power angle.

\[ Q_2 = \frac{V_1 V_2}{X_l} \cos \theta - \frac{V_2^2}{X_l} \]  

(3.27)

By combining equations (3.20) and (3.27), we can derive the expression of the receiving power as a function of the tangente $\phi$ and the receiving voltage [15]:

\[ P_2 = \frac{V_2^2}{X_l (1 + (\tan \phi)^2)} \left[ -\tan \phi + \sqrt{\frac{1}{1 + (\tan \phi)^2 \frac{V_1^2}{V_2^2}}} \right] \]  

(3.28)

From (3.28), we can derive the maximal loadability as follows:

\[ P_{\text{max}} = \frac{V_1^2}{2 X_l \cos \phi} (1 - \sin \phi) \]  

(3.29)

\[ P_{\text{max}} = \frac{V_1}{\cos \phi} \sqrt{\frac{(1 - \sin \phi)}{2}} \]  

(3.30)
On the figure 3.13, some nose curves are plotted with different values of $\tan \phi$. 

First, we can notice that the decrease in the algebraic value of $\tan \phi$ tends to increase the system operating voltage point. The line has more capacity and for a given power flow, the voltage is higher. When the voltages are quite low, especially in winter, it is possible to use shunt capacitors on the supply substations to increase the receiving voltage [16]. However an important decrease in the $\tan \phi$, by means of compensation, may lead to some instability since the operating voltage value is getting closer to the critical voltage value.

**Generator limitations**

For the previous studies we have considered a generator with no limitations. However, it is not the case in reality since the generators do not have unlimited power reserves. It is possible to represent a synchronous generator by the following equivalent circuit (here the transmission line is not represented) as shown in figure 3.14.

\[ E \] is the generated voltage
\[ X_s \] is the synchronous reactance
\[ I \] is the current

The operating domain of the generator faces different limits such as current or turbine power limitations induced by rotor or stator heating limits. We usually study a generator on a $[P,Q]$ diagram for a given stator voltage, as shown in figure 3.15.
Generators connected to the grid are equipped with different protections and regulation devices that prevent the different values of exceeding the limitations. As we are studying the potential risk of voltage collapse, the only limitation that we will take into account is the rotor current limitation since it is directly related to the generator capacity of reactive supply. When this limitation is reached, a protection loop ensures that the generator to decrease the voltage while maintaining a constant reactive supply.

In order to evaluate the impact of this limitation, we still use the simple line model as the one in section 3.2.2, but we take now into account the maximal reactive power production. We can express the formula linking the generator reactive power production $Q_1$, the receiving voltage $V_2$ and power $P_2$.

The expression of the transmitted power $P_2$ has already been given in equation (3.20). We can also express the reactive power production from diagram 3.6:

$$Q_1 = V_1 I \sin \theta$$ (3.31)
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Figure 3.15: Generator operating limitations on a P-Q diagram [17]

Where \( V_1 \sin \theta = \Delta V \)

\[
Q_1 = I_1 \Delta V = \frac{\Delta V^2}{X_l}
\]  

(3.32)

From (3.20) and (3.32), we can derive the formula linking \( V_2, P_2 \) and \( Q_1 \):

\[
V_2 = P_2 \sqrt{\frac{X_l}{Q_1}}
\]  

(3.33)

The impact of the generator limitation has been represented on the diagram 3.16.

They are two possible scenarios:

- \( I_{\text{rotor}} < I_{\text{limitation}} \) : The generator didn’t reach its reactive supply limitation yet and the curve follows the nose curve described by the equation (3.19).

- \( I_{\text{rotor}} = I_{\text{limitation}} \) : The generator cannot produce more reactive power and the system follows the equation (3.33). \( V_2 \) starts to decrease in inverse proportion to the increase of the demand. The maximal transmitted power decreases and the system is much less stable.
3.2.5 Load modeling

There are various types of loads in power systems as shown in figure 3.17. The load characteristics at each substation should represent properly the aggregate effect of all loads connected, especially since these models are directly taken into account for power flows or stability studies.

The first designed load models failed to bring a good understanding of some phenomena...
such as voltage collapses since they were not accurate enough [18]. Furthermore, different load models could give very large results differentials which emphasize the need for a more accurate model.

In addition, it is important to differ static load modeling and dynamic load modeling. For example a high proportion of the load is represented by induction motors and the behavior of such loads can only be explained through dynamical models. Static models are mostly used for steady state conditions calculations, and dynamic models for studying dynamic phenomena [19]. A brief introduction of dynamic load modeling is made in this chapter.

### Static load models

Static load models are generally defined as a function of the active and reactive power, which depend on the voltage and the frequency.

\[
P = P_0 \left( \frac{U}{U_0} \right)^{\alpha} \left( \frac{\omega}{\omega_0} \right)^{\delta}
\]

\[
Q = Q_0 \left( \frac{U}{U_0} \right)^{\beta} \left( \frac{\omega}{\omega_0} \right)^{\gamma}
\]

$P_0$ and $Q_0$ are respectively the active and reactive loads computed through the load flow computations. $U_0$ is the busbar voltage at initial state and $\omega_0$ the frequency.

Since the characteristics of the loads are not the same and so don’t have the same voltage sensitivity, the coefficients may differ between different loads, as shown in figure 3.18.

<table>
<thead>
<tr>
<th>Models</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant power</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>constant current</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>constant impedance</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 3.18: Static load models

A combination of these models is generally used to represent the loads, known as the polynomial representation [20]:

\[
P = P_0 [a_1 + a_2 (\frac{U}{U_0})^1 + a_3 (\frac{U}{U_0})^2] 
\]

\[
Q = Q_0 [a_4 + a_5 (\frac{U}{U_0})^1 + a_6 (\frac{U}{U_0})^2]
\]

Where $V_0$, $P_0$ and $Q_0$ are the values at the initial conditions and the coefficients $a_1$ to $a_6$ are the parameters of the system.

We can notice that the results of a stability study are different regarding the coefficients taken in the equations 3.36 and 3.37, so it is important to have an accurate model which reflects
realism as well as possible.

Figure 3.19 shows us the influence of static load models on the nose curve after a disturbance (line tripping for instance). We can notice that when $\alpha$ is decreasing, the new operating point is closer to the critical point and so voltage stability is more affected. This is particularly the case when $\alpha$ equals $-0.5$.

**Dynamic load models**

We have studied in the first section the static load models which gives a good overview of the loads behavior. However, some loads such as electric heating would tend to recover the initial power (at the pre-disturbance state) after the drop of voltage induced by the line tripping. An approach of this dynamic response can be represented by the equations 3.38 and 3.39, [19].

\[
T_p \frac{dP_r}{dt} + P_r = P_0 \left( \frac{U}{U_0} \right)^{\alpha_t} - P_0 \left( \frac{U}{U_0} \right)^{\alpha_s} \tag{3.38}
\]

\[
P_l = P_r + P_0 \left( \frac{U}{U_0} \right)^{\alpha_s} \tag{3.39}
\]

Where $U_0$ and $P_0$ are the voltage and the consumption at the initial conditions, $P_r$ is the active power recovery, $P_l$ is the total active power, $T_p$ is the active load recovery time constant, $\alpha_t$ is the transient active load-voltage dependence and $\alpha_s$ is the steady state active load-voltage dependence. An approach of the load evolution after disturbance is represented in figure 3.20.

The power increasing can be seen by a decreasing of the coefficient $\alpha$. However, it $\alpha$ decreases too much, there is a risk that the requesting power becomes higher than the critical point of the figure 3.19.
3.3 Voltage control mechanisms

3.3.1 Introduction

We have seen in the section 3.2 that it is important to control voltage, in order to maintain supply voltage within contractual agreement or to respect the various equipment constraints, and also to minimize losses and use the capacity of power facilities as well as possible. The voltage drop is really dependent on reactive power flows, therefore to control the voltage it is necessary to compensate in the same way the reactive power. This is the role of load compensation to improve the quality of supply in ac power systems [21], whose 3 main objectives are:

- Power-factor correction
- Improvement of voltage regulation
- Load balancing

In that way we could define the ideal compensator as the device capable of performing those three functions, with an ability to respond instantaneously to variations. It means that this capacitor would have the property to provide a controllable and variable amount of reactive power, would present a constant voltage at its terminal and would be able to operate independently in the three phases.

It exists today different types of compensating equipments each with specific properties. For instance, the compensation on the distribution network (on the supply substations) is mainly made from shunt capacitors. Regarding the transmission network, the reactive power compensation is mainly ensured by the connected generators. However, since production is usually far from the load, it is also necessary to use passive control equipments such as capacitors on
the transmission grid in order to relieve the groups action and to offer more power capability through the lines. When the transmission network tends to be rather reactive power producer, the use of reactors can be needed. Finally, synchronous condensers are effective control devices which have the possibility to both supply or absorb variable reactive power.

The generators reponse time is very short and therefore they can adapt instantly their reactive power supply in a very precisely. On the contrary, capacitors which have a much longer response time, are mainly used to follow periodical fluctuations. Then it is important to precise that the reactive power production from a capacitor decreases proportionally to the square of the voltage. The generators regulation is supervised by three levels of voltage control that are spatially and temporally independent in order to avoid contradictions between the different actions conducted:

- **Primary Voltage Control**: All generators are equipped with a primary voltage controller which gives them the ability to control their stator voltage at set points, by varying their excitation current. Obviously this control is operational within the constructive limit of the generators. This automatic device has a very fast response time and is therefore the most efficient mean of voltage control, particularly to deal with random load fluctuations.

- **Secondary Voltage Control**: The Primary Voltage Control is a purely local mechanism and a centralized control is consequently necessary to coordinate the actions of the network’s generators. In fact, after a disturbance, the local regulation enables the generators to adjust their stator voltage but it is usually a non optimum solution for the overall network, where a generator may for example produce reactive power partially absorbed by another one. Contrary to the primary voltage control, the time-scale of this mechanism is around few minutes.

- **Tertiary Voltage Control**: The last voltage control aims to rehabilitate secondary voltage set point levels following the continuous changes of operating conditions. Thus it enables the system to be operated at an economic optimum and avoid also degraded network operation. It is usually a manual process but it can be automatized with a time-scale of at least 15 minutes.

### 3.3.2 Secondary Voltage Control

As shown in figure 3.21, the main interest of the Secondary Voltage Control (SVC) is to control the voltage value inside a specific geographical area. A pilot point is defined in each area and if the pilot point voltage differs from the set point voltage, an automatical order is sent to the groups which belong to the area in order to adjust their reactive power production. Generally speaking, this is a set of generators controlling by a pilot point that defines a SVC area.

In France, there are 35 pilot points and the voltage control in a specific area is totally independent from the others. Then a pilot point should be sufficiently representative of the overall area and shouldn’t be too close of the units. For each zone a signal N, which represents the required reactive power level for the zone, is computed in the regional control centers by applying a proportional integral law to the difference between the pilot point set-point voltage and the pilot point voltage measurement. Then this level N is sent to all the units every 10
seconds and is used to determine a set-point for the reactive power loop of each unit, as shown in figure 3.21. The reactive power loop increases or decreases the terminal voltage set-point of the primary voltage controller, regarding the input parameters such as the level N or the current reactive power production of the generator.

Thus the SVC enables to increase the efficiency of the Primary Voltage Controller and also to coordinate the groups actions in a same area, particularly after a disturbance. It is then possible to get the steady-state reactive power generation aligned, as long as a generator limit is not reached. However, the Secondary Voltage Control has also some drawbacks:

- The level N sent to the generator is exactly the same (for a given area) which is usually not the best optimum regarding the economic or the safety aspects. This is especially the case when a generator reaches its physical limitations (such as the rotor current limitation) and doesn’t participate anymore to the secondary control.

- The parameters of the reactive loop are fixed and should be adapted regarding the operating conditions.

- The SVC presents also an adverse effect on the reactive loop which is slower than the primary control and which sometimes delays the reactive power production of the generator after a disturbance.

A new Secondary Voltage Control has been developed in order to eliminate these different drawbacks. This new mechanism is the Coordinated Secondary Voltage Control (CSVC). At this moment, the CSVC was implemented only in the Western are of the frend grid, in the regional control center, since this is the part of the network where the voltage constraints are the most important. The new control, contrary to SVC, has the possibility to adjust the voltage map of a given region by regulating the voltage values at a set of pilots points. The CSVC computes directly, for each group, the terminal voltage variations to apply at its Primary Voltage Regulator. The CSVC used an algorithm whose main variables are:
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- the difference between pilot points voltage and their set-point value
- the difference between each group’s reactive power production/stator voltage and their set-point values

While taking into account:
- the network constraints
- the groups operating diagram
- the possible set-point variations of the primary regulator

As a result, the major interactions between areas are taken into account, and the adverse effect of the reactive loop doesn’t intervene anymore since the set-point voltage is directly computed at the control center and then sent to the groups. The voltage map is also more stable and more accurate following disturbances. The dynamic of the mechanism is also much faster than the former one.

3.3.3 On-load tap changers

Another system widely used to control the voltage is the On-Load Tap Changer (OLTC). In order to fulfill the requirement in terms of electricity quality, and since these requirements are not the same in the transmission and the distribution grid, it is necessary to decouple as well as possible those two networks. The OLTC enables to keep the distribution voltages in a suitable range independently of the voltage variations in the transmission grid.

Practically all power transformers and many distribution transformers are equipped with On-Load Tap Changer which enables them, while being on duty, to change their turns ratio \( tr \) between windings and therefore to control the transformer output voltage, as shown in figure 3.22. In that way, the transformers have taps, in one or several winding, bounded by an upper limit and a lower limit, and connected to the OLTC. By varying the tap position, the turns ratio \( tr \) of the transformer can be changed and therefore the secondary voltage is continuously adjusted.

At every moment, the secondary voltage is compared to the set-point value. If the voltage measurement is lower (respectively higher) than the requirements, the OLTC is engaged. After a certain time, which varies regarding the voltage levels where the transformers are connected to, the tap number increases (decreases) one by one, and this operation is repeated until the voltage measurement matches the half-deadband or until the OLTC reaches one of the limits.

At any moment we have:
- \( V_3 = V_2/tr = V_{Load} \) if the OLTC is operating between its limits
- \( V_3 = V_2/tr_{max} \) if the OLTC reaches the lower limit
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\[ V_3 = \frac{V_2}{tr_{\text{min}}} \] if the OLTC reaches the upper limit

With:
- \( V_{\text{Load}} \): load voltage (set-point voltage)
- \( V_2 \): primary voltage
- \( V_3 \): secondary voltage
- \( tr_{\text{max}} \): highest turns ratio
- \( tr_{\text{min}} \): lowest turns ratio

The OLTCs don’t have the same activation points, depending on the voltage levels they are connected to. Below is a table that sums up the different specifications:

<table>
<thead>
<tr>
<th>characteristics</th>
<th>EHV/HV</th>
<th>EHV/MV</th>
<th>HV/MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap numbers</td>
<td>25</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>First delay</td>
<td>30 seconds</td>
<td>1 minute</td>
<td>1 minute</td>
</tr>
<tr>
<td>Subsequence delay</td>
<td>10 seconds</td>
<td>10 seconds</td>
<td>10 seconds</td>
</tr>
</tbody>
</table>

To illustrate the behaviour of the OLTC, let us consider the following situation. A generator (without any limitation) is currently supplying, through a double line, a load \( R \) at a set-point voltage \( V_{\text{Load}} \). The nose curve at initial conditions 'state 0' is plotted on the figure 3.23.

At any moment, the equations linking the variables upstream and downstream of the transformer are:

\[ tr = \frac{V_2}{V_3} \quad (3.40) \]
Figure 3.23: Nose curve

\[ P_3 = P_2 = \frac{V_3^2}{R} \]  \hspace{1cm} (3.41)

\[ V_2 = trV_3 = tr \sqrt{R \times P_2^2} \]  \hspace{1cm} (3.42)

Then, the initial conditions give:

\[ P_3 = P_2 = P_{\text{Load}} \]  \hspace{1cm} (3.43)

\[ V_2 = tr_{\text{init}} \sqrt{R \times P_{\text{Load}}^2} \]  \hspace{1cm} (3.44)

Where \( tr_{\text{init}} \) is the initial turns ratio.

Equation (3.44) is represented as the green dotted curve. The intersection between this curve and the nose curve "state 0" gives the initial operating point A.

We still consider the same system but now, one of the line triggered suddenly, changing in the same way the initial characteristic of the nose curve, plotted as the "state post-disturbance" nose curve. We can notice that after this disturbance, the voltages \( V_2 \) drops and the delivered active power \( P_2 \) drops in the same way. It turns out that the load is not supplied anymore in good conditions since only \( P_f \) is transmitted (point B). The OLTC gives the order to decrease the turns ratio in order to increase the receiving voltage \( V_3 \). As a result, the power \( P_2 \) increases little by little until reaching the initial power \( P_{\text{Load}} \), when \( tr \) reaches \( tr_{\text{final}} \) (point C).
The final state is:

\[ P_3 = P_2 = P_{Load} \quad (3.45) \]

\[ V_2 = tr_{final} \cdot V_3 = tr_{final} \cdot \sqrt{R \cdot P_{Load}^2} \quad (3.46) \]

After the disturbance, the OLTC enables the system to find a new equilibrium point that meets the load requirements, despite the decreasing of the upstream voltage \( V_2 \). Furthermore, this recovery was possible because the maximal transmissible active power was sufficient, even with only one single line. We will now study the case where the resulting system after disturbance doesn’t allow to transfer \( P_{Load} \).

We consider exactly the same situation and the same disturbance. The initial conditions are exactly the same as previously (point \( A \)). However in this case we consider that the requesting active power is higher than in the first case.

We can notice that the load \( P_{Load} \) exceeds the maximal transmissible power of the post-disturbance nose curve.

In the same way as previously, the OLTC measures a difference between the delivered voltage and the set-point voltage, and so gives the order to decrease the turns ratio (point \( B \)). At the beginning, the transmitted power increases (as the voltage \( V_2 \) decreases) and the delivered voltage increases in the same way until \( P_2 \) reaches the maximal transmissible power \( P_{max} \), (point \( C \)). However, the load voltage still didn’t reach the set-point value and the OLTC still gives the order to decrease the turns ratio. Therefore, the voltage \( V_2 \) continues to decrease.
but now the delivered power is also decreasing (point $D$). We are witnessing a voltage collapse and the OLTC is now operating at conditions which are worse than before its intervention. To avoid the OLTCs to lead to a voltage collapse, some devices are used to block automatically the OLTC when the voltage decreases below a lower limit.

### 3.4 Prevention of voltage instability

#### 3.4.1 Contingencies and margins

The power system is continuously subjected to contingencies that can be organised in four groups [22]:

- Load variations
- Outages (unforeseeable equipment failures)
- Meteorological hazards (lightning, storms)
- Human factor

As a result it is necessary to ensure protection against these contingencies by setting up different security margins (such as the $N - k$ rule), that guarantee reliability despite the contingencies listed above. However, TSO cannot afford to provide protection against all types of contingencies, since these additional measures are usually costly and since the number of combinations is too wide. It means that the system reliability cannot be ensured at any price but has to follow the occurrence probability of contingencies.

The system reliability has to obey to the $N - k$ rules which defines the maximum accepted risk level and more particularly the $N - 1$ rule, which states that the loss of an element on the network shouldn’t lead to an extent of potential power cut. As an example, the system reliability shouldn’t be degraded after a line loss or a group loss. Then simulations are made to compute the right estimation of load transfers in case of contingencies $N - k$ to avoid cascade tripping.

#### 3.4.2 Reliability degradation: Voltage Collapse

Despite the margins set up above, in some cases, it might happen that a series of contingencies leads to a large scale phenomenon resulting in a reliability degradation. Those contingencies can be classified as follows:

- Cascade Tripping
- Voltage collapse
- Frequency collapse
- Loss of synchronism
CHAPTER 3. THEORETICAL STUDY

As seen in the section 3.2.1, the voltage is a local magnitude dependent on the load fluctuation and more particularly on the variation of reactive power flows. After a contingency (generation unit or line tripping), the reactive sources in a given area may not be sufficient anymore to supply the load (due to the generators rotor current limitations or a lack of capacitors for instance). Therefore the area has to import the needed power from neighbouring areas, and therefore, this may lead to voltage drop. The OLTCs in turns change the tap positions in order to keep the consumers’ voltages in the acceptable level. As a result, the line current increases and so the reactive consumption as the power flows increases.

In addition, if the reactive power demand of the area exceeds the capacity of the neighboring zones, then they have to import in turns reactive power from other areas and they will undergo the same constraints than the first area. If the phenomenon continues to spread on the network, the voltage magnitudes may reach critical values, which can have the consequence of limiting drastically the active power flows and ultimately leading to a voltage collapse.

During a phase of voltage collapse it can be sometimes necessary to use ultimate measures [22]:

- Blocking automatic the OLTC of EHV/HV and HV/MV transformers
- Lowering the MV voltage level by 5%
- Start-up of rapid means of generation
- As a last resort, the load shedding

3.4.3 Under Voltage Load Shedding

The main goal of the LSD is to shed pre-selected loads within an area with significant voltage drops due to a disturbance [24]. The LSD is usually set up in areas with a high consumption and few production units because they are more likely to lead to voltage collapses. There are two different types of load-shedding schemes:

- The distributed under-voltage load-shedding scheme: every load to be shed is equipped with protection. Thus, the load-shedding is made directly at the origin of the perturbation.
- The centralized under-voltage load-shedding scheme: critical buses inside a given area are measured and if the voltage value of at least one bus goes down a critical limit, then the load shedding device sends orders to shed the entire area.

The table 3.1 introduces the drawbacks and the advantages of each scheme:

In France, the electrical network is organized in seven areas (see figure 1.3) and all the loads within an area have been splitted into subzones called ACR (Regional conduct agency) or load areas. Before setting up the LSD, we define a reference node (or several) for each load area. The role of the LSD is to monitor the voltage at these reference nodes, and if the voltage of a given node decreases below a critical value, then the LSD sheds loads in the area on which the reference node was measured. The load shedding is made in three steps, where a percentage of load will be shed after a certain measurement time for each step. The diagram 3.25 can help to understand how works the LSD with different monitoring nodes $V_i$. 
### CHAPTER 3. THEORETICAL STUDY

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Distributed load-shedding</th>
<th>Centralized load-shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advantages</td>
<td>→ Mal-operation of one component doesn’t affect other protection component.</td>
<td>→ Different measuring relays located at the most appropriate points.</td>
</tr>
<tr>
<td></td>
<td>→ Load shedding concentrated in the weakest area.</td>
<td>→ Can use other indicators such as power flows or loss of lines.</td>
</tr>
<tr>
<td></td>
<td>→ No communications facilities needed so higher reliability.</td>
<td>→ Less equipments so lower investments spent in the system reliability.</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>→ More expensive, since many equipments set up at many locations.</td>
<td>→ Depends only on few or one component, and only one fault of the scheme may lead to the invalidation of the whole scheme.</td>
</tr>
<tr>
<td></td>
<td>→ Only the node voltage as indicator.</td>
<td>→ The load is shed whether the voltages at the load delivery nodes are low or not.</td>
</tr>
</tbody>
</table>

Table 3.1: Advantages and Disadvantages of load shedding schemes

1. The different monitoring node values $V_i$ are constantly measured

2. If one of the nodes values $V_i$ is lower than the threshold $V_{t_{down}}$ during $t_m$, then a load shedding order is sent and the load shedding is achieved after a delay time $t_d$. (If the voltage restores above the same threshold $V_{t_{down}}$ before the end of the measurement time, the device is reset and starts again the level process)

3. After a load shedding, the device takes a 5-second break and then the same operation is performed again. This operation is repeating three times at the most.
CHAPTER 3. THEORETICAL STUDY

Initial state

1. Monitoring key points voltage $V_i$

   2. Is $V_i < V_{t\text{down}}$ during $t_m$?
      - yes
      - no

   3. $X\%$ load shed (after $t_d$)

   4. Three load shedding done?
      - yes
      - no

   5. wait 5s

Figure 3.25: Operating principle of the load shedding device
Chapter 4

Simulation tools

4.1 Convergence

Convergence is the name of a platform equipped with different tools which has the particularity to provide as well load flow computations (HADES) as slow dynamics simulations (ASTRE).

4.1.1 Convergence’s static tool: HADES

HADES is a module essentially designed for load flow calculations. It gives the possibility to make a load flow from an initial state of the system \(N\) and after one or several faults \((N - 1)\). For example, we can compute a load flow after a line or a generator tripping, which can be useful if we want to see if a given fault can lead to one or several overloaded lines. Furthermore, HADES gives the user the possibility to try many scenarios, by increasing or decreasing the consumption in some areas. The user can also decide to use or not the OLTC. From a given situation, it gives the possibility to change some inputs parameters such as :

- Network topology
- Active and reactive power injections
- Components characteristics
- Groups diagram
- Automatons’ operation
- Load Tap Changers setting

Then the load flow calculations gives a network map whose main characteristics are :

- Voltage, Angle at each node / Voltage constraints
- Active and reactive power flows / Power flows constraints
- Generators constraints such as low stator voltage.
4.1.2 Convergence’s dynamic tool: ASTRE

ASTRE is the Convergence’s dynamic tool developed by the University of Liege in Belgium. The power of ASTRE stands on its Quasi Steady State Simulation (QSSS) module. It is time domain simulation module which models the system slow dynamics using the quasi-steady approximation. This approximation consists by representing faster phenomena (for example induction motors or HVDC components) by their equilibrium conditions instead of their full dynamics. In parallel, it is possible to focus the attention on the long-term dynamics for example the OLTC dynamics or the secondary voltage control. The general dynamic model of the power system can be described by a set of four equations [25]:

\[
\begin{align*}
0 &= g(x, y, z_D, z_C, \lambda) \quad (4.1) \\
\frac{dx}{dt} &= f(x, y, z_D, z_C, \lambda) \quad (4.2) \\
z_D(k + 1) &= h_D(x, y, z_D(k), z_C) \quad (4.3) \\
\frac{dz_C}{dt} &= h_C(x, y, z_D, z_C) \quad (4.4)
\end{align*}
\]

The algebraic equation (4.1) represents the network equation and (4.2) represents the short-term dynamics equation (such as synchronous machines) and is equal to zero with the QSSS approximation. Both equations involve the transient state variable \(x\) and the algebraic variable \(y\), which relates to network bus voltage magnitudes and angles. \(z_D\) relates to discrete controls such as tap changers and \(z_C\) represents continuous load recovery dynamics. Finally, \(\lambda\) denotes changes in demand and the corresponding generation rescheduling. The long-term dynamics are modelled by the equations (4.3) and (4.4), involving discrete and/or continuous time variables respectively.

In order to perform a simulation with ASTRE, we first have to make a load flow with HADES. Then ASTRE gives the possibility to make the load vary in different areas (this step is known as the load variation). And in a last step, the scenario assesses the dynamic evolution of the network after disturbance. The three states are:

- state \(N\) : after the load flow
- state \(t_0\) : after the load variation
- state \(t_{fin}\) : after scenario

Even without any change of load between the state \(N\) and the state \(t_0\), both states are different since \(t_0\) state is made from a dynamic simulation and, as a result, the system takes now into account all the generators regulations (primary and secondary voltage control), the transformer dynamics with the tap changing and other automaton regulation. Another function that is frequently used on ASTRE is the computing of security limits with the margin calculation module. This module can determine the secure operation limit, described as a type of
CHAPTER 4. SIMULATION TOOLS

security limit which indicated how far the system can be stressed prior to any contingency such that it remains stable after the contingencies. In order to perform a computation, we first have to define a set of disturbances, a maximal consumption increase, a stopping criterion and a tolerance for the results.

4.2 Eurostag

Eurostag is a very fast dynamic tool developed by RTE and TRACTEBEL which was at first designed to perform electromechanical transient simulations. Today Eurostag is used to perform power system dynamic simulation for transit, mid and long-term stability and so is very powerful for voltage stability studies.

This software integrates all power system components and actions necessary to produce an accurate dynamic simulation. Moreover, Eurostag is based upon only a unique powerful algorithm (no distinction between slow and fast dynamics) using a continuously and automatically varying integration step size [26]. This gives the advantage for Eurostag to own only a unique model and to perform various type of simulations from electromechanical oscillations (after a line trip or a short-circuit) up to daily load evolution.

Eurostag can make both load flow and dynamic simulation. Before performing a dynamic simulation, it is necessary to initialise the studied situation by doing a load flow calculation. In order to ensure this, the user has first to give an input file .ech to the program. This file contains various information regarding the buses (voltage, injected power, angle), the lines and the transformers with their characteristics for example. If the load flow calculation converges, the user gets a file .lf that is used to perform dynamics simulations. In addition to the file .lf, the user has to provide a file .dta (which contains informations regarding the generators with their regulators or the SVC for instance) and a scenario file .seq which specifies the different events simulated. After the simulation, the user has at its disposal a graphical interface to analyse all the physical variables of the system.

In conclusion, the power of Eurostag stands in its ability to perform as well load flow calculations, long-term and short-term dynamic simulation. Then the major advantage is the variation of the time step which is constantly adapted to the system state. If the system has to undergo oscillations or very fast variations, the time step is instantly decreased to get accurate results, whereas flat conditions tends to increase the time step. The user-friendly Eurostag’s interface makes it easy for the user to add new models to the main library and so it is very convenient for adapting the software to the continuous evolution of the network.
Chapter 5

Test of the SMACCs

5.1 Presentation of the SMACCs

5.1.1 Context for this new control system

In order to improve the reactive power compensation on the network, various batteries of shunt capacitors were installed by EDF before the 2000s. The batteries were located very close to the load on the distribution network and more particularly on sources substations, to reduce the reactive flows and so to reduce the important voltage drops. Since the separation between EDF and RTE, RTE decided to set up batteries on its transmission network in order to reduce the reactive power flows and in a same way to relieve the generators actions.

The batteries of capacitors have been set up first on the repartition network on high voltage levels such as 63/90 kV. Then, in order to compensate the important reactive losses on the EHV network, RTE is now extending its batteries on higher levels (225/400 kV). RTE firstly decided to use batteries only on one voltage level (on a given substation) but this has changed for several years since batteries are now set up on both 225 kV and 400 kV levels and sometimes more. Today, many capacitors have already been set up and it is planned to extend the amount of those compensations means in order to reach a total capacity of 10 000 MVar in 2017 in the whole territory and about 3000 MVar in CESO (South-West grid in France).

Those batteries have always been controled by a device called "ACMC" (Automate pour le contrôle de la compensation - Automaton for the control of compensation means) which connects or disconnects the capacitors following a voltage criterion. A manual control is also available from the dispatching centers. This device have always provided good results since batteries were located on one unique voltage level.

Nonetheless, due to the growing number of capacitors on the network as well as the presence of batteries on different voltage levels within a given substation, it is today necessary to find a new control of the compensation in order to guarantee a coherence between the connection and disconnection of capacitors and to ensure a maximum of reliability and security. A new device, called "SMACC" (Système avancé pour la commande de la compensation / Advanced system for the control of the compensation ), has consequently been developed. Contrary to the ACMC, the SMACC will have the possibility to measure the voltage values on both 225 kV and 400 kV
voltage levels and to act accordingly. Only one SMACC is used per substation to control the various batteries in this same substation. Today, some SMACC devices have already been set up in the South-West and the North grids in France. In the long term it is even supposed to replace the ACMC.

In order to better understand the goal of the SMACC, the ACMC is first described. Usually, we use batteries of 80 MVar on the 225 kV nodes and batteries of 150 MVar on the 400 kV nodes. The control of those batteries by the ACMC is quite simple. As shown in figure 5.1, the ACMC can control the capacitors following a voltage criterion.

Three cases can be encountered depending on the voltage value:

- If $V_{\text{node}} > V_{\text{upper}}$, the ACMC disconnects a capacitor (if at least one capacitor was connected initially)
- If $V_{\text{lower}} < V_{\text{node}} < V_{\text{upper}}$, no action is made
- If $V_{\text{node}} < V_{\text{lower}}$, a capacitor is connected (if at least one capacitor is available)

The capacitors are connected or disconnected one by one by the ACMC. A delay time is also introduced before each action of the device. It means that the voltage conditions, as mentioned above, must be valid as long as the duration of the delay time so that the ACMC can connect or disconnect a capacitor.

In order to introduce the necessity to use a new automaton (the SMACC) for the control of the capacitors, the limits of the ACMCs have been highlighted in the following example.
The ACMC can only control one voltage level and if we want to control batteries of capacitors connected on both the 225 and 400 kV in a given substation, it is necessary to use two ACMCs (each device controls one type of batteries). In this example, we consider a substation where batteries of capacitors are connected on both 225 and 400 kV levels. The figure 5.2 shows the resulting diagram, which combines two ACMC diagrams (225 and 400 kV) represented in figure 5.1. We can distinguish three different types of actions:

- The central part (represented in green) represents the normal operating area, where no actions are needed.
- The white blocks represent the action of only one ACMC.
- The blocks on the corners (in red) represent simultaneous actions between both ACMCs.

Combining two ACMC devices presents some drawbacks: the ACMCs just take into account the voltage on one node but not the voltage on the other nodes of the substations. Consequently, there is a risk that two ACMCs disconnect simultaneously two batteries in a same substation (on the 400kV node and on the 225kV node) whereas disconnecting just one would be enough and would have led to more safety. Then, the connection of one batteries on a given voltage level can lead to the disconnection of a batterie on another voltage level and so on. Using two different devices doesn’t allow a good coordination between the connection and the disconnection of all the batteries present in the substation. That is why with the arrival of the new compensation means (mainly on the 225 kV and 400 kV levels) in the upcoming years, it is necessary to upgrade the control systems to avoid bad interactions between the connection and the disconnection of capacitors.
5.1.2 Operating principle

The figure 5.3 represents the SMACC operating diagram. In the same way than for the ACMCs diagrams, it is possible to distinguish the green area for the normal operating state (no actions), the white blocks for the connection or the disconnection of a capacitor on only one voltage level and the red frame which represents the security actions of the device. There is in reality a deadband (where no actions can be taken by the SMACC) between the red frame and the other blocks of the diagram to avoid inappropriate capacitors switching in case of voltage swings for instance. The SMACC (unlike the ACMC) can measure the voltage on both 225 and 400 kV, and as a result it is more efficient to manage the connection or the disconnection of capacitors. For instance, if the voltage value on the 225 kV level is low but the one on the 400 kV is already very high, the SMACC avoids a connection of capacitors on the 225 kV level and as consequence provides more security. Another advantage in the SMACC operating diagram is the use of prioritizations for the connection or the disconnection of batteries, as shown in the block n°1 in the diagram 5.3. For example, if the voltage map is inside the block n°1, the SMACC starts by connecting capacitors 400 kV one by one, and if there are no more capacitors 400 kV and if the voltage map is still in the block n°1, the SMACC connects capacitors on the 225 kV level.

The SMACC device uses different temporisations depending on the node level and the type of switching (connection or disconnection) as shown in table 5.1. This difference between the delay times aims to avoid simultaneous actions of the SMACC in particular with the prioritization management. The delay time is defined as the time during which the mean value has to stay in a block before an action of the SMACC. Those delay times in table 5.1 are the original one and a part of the study is to evaluate if they are suitable.
CHAPTER 5. TEST OF THE SMACCS

<table>
<thead>
<tr>
<th>Voltage levels</th>
<th>400 kV</th>
<th>225 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection</td>
<td>5 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>Disconnection</td>
<td>10 sec</td>
<td>8 sec</td>
</tr>
</tbody>
</table>

Table 5.1: Delay times

Furthermore, when a capacitor is disconnected, it is necessary to wait 300 seconds which corresponds to the time of full discharge of the capacitors (time needed by the capacitor to be operational once again). This property is seen as a physical constraint for the study and this shows us that we have to disconnect a capacitor only if it is really needed.

5.1.3 Challenges

The first part of the study is to develop the models of the SMACCs in both Convergence and Eurostag. The models has to give the possibility to change easily the parameters of the SMACC such as the voltage thresholds or the delay times. Then the major part is devoted to the dynamic simulations in Convergence and Eurostag. The aim of this study is to validate or to change the original parameters that defined the SMACC. Then, since there are different substations where the SMACCs are supposed to be installed, it may also happen that two SMACCs don’t have the same parameters to avoid bad interactions.

5.2 SMACCs study

5.2.1 Preparatory work

Situation studied

All the simulations are made from the situation of the 9th of February in 2012, at 9 am. During this day, France was importing a lot a power from neighboring countries. Particularly, CESO (South West region of France) was importing more than 1000 MW from Spain and more that 4000 MW from neighbouring regions. By causing appropriate faults in such conditions, we have the possibility to see if the SMACC contributes correctly to the system stability recovery.

Methodology

Before doing each dynamic simulation, it is necessary to run first a load flow computation. Several setups can be tested regarding the number of capacitors initially connected. At this moment, the SMACCs are not yet introduced in the system. After the load flow and if all buses have voltage in a good range, it is then possible to run dynamic simulations. If the voltages conditions are not respected, then a new setup is tested by disconnecting or connecting some capacitors. The aim of using different setups is to study the behavior of the SMACC according to different initial conditions.
When the load flow is done, it is possible to run dynamic simulations. In that way and to evaluate the behaviour of the SMACCs, it is necessary to simulate a suitable scenario. The fault tested for almost all the simulation is a double line tripping and is introduced in figure 5.4.

![Figure 5.4: Choice of the fault: Double line tripping](image)

Capacitors are connected both on substation 1 and substation 2 and consequently a SMACC is also present in each substation. By disconnecting suddenly the line between substation X and substation 1, a peak of voltage is induced after the fault at substation 1 and 2, which tends to make some capacitors disconnected due to the actions of both SMACCs. Then, the loss of the axis between substation X and substation 1, which is essential for the system stability, causes in most of cases a voltage collapse. This fault is therefore well adapted to set up the SMACCs is used for simulations on both Convergence and Eurostag.

5.2.2 Simulation on Convergence

The first study of the SMACC is made on Convergence. Since the time step in Convergence is 10s, all the delay times that define the SMACCs are then equal to 10s. As a result it is not possible to study the SMACC with the original delay times (defined in section 5.1.2). Therefore this study is just a preliminary analysis before the one in Eurostag. Then, the simulations made in order to test the SMACC may not reflect pure reality in the sense that more capacitors are sometimes set up at different voltage nodes. In fact it is very challenging to evaluate the model with only one or two capacitors in each node. Besides the SMACC is supposed to receive 4 capacitors at each voltage level and I am still in this range when running the simulations.

After doing some simulations on Convergence, it appears that sometimes the SMACCs tend to disconnect more capacitors than necessary. In fact after the disturbance (introduced in section 5.2.1), the peak of voltage is so high that 2 capacitors on substation 1 as well as one capacitor on substation 2 can be disconnected, as shown in figure 5.5. This phenomenon is bad for the system stability since 3 capacitors are then disconnected during 300 seconds (time...
needed before re-activating the capacitor).

In the figure 5.5, it is possible to see the peak of voltage at $t = 150s$ due to the line tripping. Then 3 capacitors are disconnected by both SMACC 1 and SMACC 2 and the voltage drops instantaneously. After the capacitors disconnection, the voltages continue to decrease due to the actions of the OLTC. The three capacitors are finally connected at $t = 450s$ (300s after their disconnection).

To overcome this problem, it may be useful to impose different delay times to the SMACCs located on substation 1 and substation 2. In a general way, we can extend this measure to the SMACCs that are located in nearby substations. By doing this, the idea is to give more time to one of the SMACCs before disconnecting a capacitor. In fact, if a SMACC has already disconnected some capacitors, it may sometimes not be necessary that another SMACC disconnects its capacitors in turn and thus that may ensure the system to keep a higher voltage map. In order to avoid the disconnection of capacitors in both substations, the delay times of the SMACC in substation 2 is increased. Since the time step is $10s$, the delay time for SMACC 2 is now equal to $20s$. As a result, the SMACC located in substation 1 disconnects its 2 capacitors as expected, and 10 seconds later, SMACC 2 doesn’t have to disconnect a capacitor since the voltage map has already dropped (as shown in figure 5.6).

In the figure it is possible to see the same peak of voltage after the disturbance than in figure 5.5, and only two capacitors are disconnected since SMACC 2 has now a longer delay time. This improvement tends to lead to a higher operating point at the end of the simulation.

This first approach on Convergence gives us good suggestions of analysis, even if the accuracy of Eurostag is needed to really evaluate the parameters of the SMACCs. As a result, further
testing in Eurostag is made on the interactions between the SMACCs which are located on neighbouring substations.

5.2.3 Simulation on Eurostag

Calibration

First of all, before studying the SMACC on Eurostag, both situations on Convergence and on Eurostag have to be calibrated. In fact, a Convergence file is first created from data collected by the SRC (Regional Control System) all 5 minutes. Then, from this Convergence file, it is possible to export all data and convert them in a format that Eurostag will be able to read. However the conversion is never perfect and we can sometimes notice some differences between those 2 files. The Eurostag file is modified in a second phase (mainly the Spanish network) to get the same voltage map in France and the same active and reactive power flows.

This has been made for example by:

- increasing or decreasing the active power of different plants
- changing various units’ stator voltage set points, in order to change their reactive production
- changing the production and consumption in Spain in order to get the same export of power in both files (Convergence & Eurostag)

SMACC implementation in Eurostag

Once the calibration has been done, it is then possible to test the model of the SMACC. The model is introduced in the following example and the attention is mainly focused on the pri-
CHAPTER 5. TEST OF THE SMACCS

For the example, a fictitious reactive load is created and connected to the substation where a SMACC and 6 capacitors (2 capacitors on the 400 kV node and 4 on the 225 kV node) are also located. The capacitors are not connected initially. At $t = 5s$, the reactive load increases suddenly, which has for consequence to decrease the nodes voltages. The new operating point (an operating point is defined by the voltages on the level 225kV and 400 kV) is, after variation, located in the block 1 of the operating diagram (see figure 5.3) which imposes a capacitor connection on both levels with a prioritization on the 400 kV. It means that if after the corresponding delay times, no capacitor on the 400 kV is available, a capacitor on the 225 kV is connected.

![Figure 5.7: Voltages at a given substation (node 400 and 225 kV)](image)

As shown in figure 5.7, the voltage decreases on both levels (225 and 400 kV). Then the figure 5.8 shows us the different temporizations after disturbance which corresponds in fact to the delay times of the SMACC. It is important to say that if at any moment the operating
Figure 5.9: Switching orders

point goes back to the normal operating area (or another area which doesn’t allow a capacitor connection), then the temporisation is supposed to reset. The red curve (respectively green curve) corresponds to the temporisation on the 400 kV level (respectively 225 kV level). At \( t = 6s \), we can notice that both temporisations start, meaning that capacitors are available on both levels. The temporization should have started at \( t = 5s \) but there is a delay of 1s due to the transient phenomenon and the computation. Then 5 seconds later, a 400 kV capacitor is connected (as a result, the voltage increases in figure 5.7) and both temporizations reset. The figure 5.9 represents the switching orders sent by the automaton. The operation starts again but at \( t = 17s \), only 225 kV capacitors are available and 10 seconds later a capacitor on the 225 level is connected.

Strategy

The analysis of the SMACC in Eurostag doesn’t focus only on the SMACC but aims also to study the environment in which the device is integrated. It means that for each relevant simulation, a detail analysis is made like the study of the units production (active and reactive power), the working of the SVC as well as the study of the on-load tap changers.

As for the simulations in Convergence, different setups are tested regarding the number of capacitors initially connected before the fault. The different setups are first tested by a load flow calculation without the SMACC. Then, the same fault (introduced in section 5.2.1) is simulated on the different setups. For each setups a color code is given in order to facilitate the comparisons of the results. Finally the impact of the HVDC line between France and Spain is also evaluate in parallel.

SMACC analysis

Simulation 1 : Original situation without HVDC line  For this first simulation, no changes are made in the original situation and the HVDC line is not taken into account. Three setups are studied and they are all represented in the table 5.2. The table 5.2 gives the number of capacitors connected initially at substation 1 and substation 2. The total number of capacitors present in each substation is represented table 5.3. A given color has been assigned for each setup. We can notice for example that the red setup has the most capacitors connected initially.
CHAPETR 5. TEST OF THE SMACCS

Table 5.2: Capacitors connected initially

<table>
<thead>
<tr>
<th></th>
<th>Substation 1</th>
<th>Substation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400 kV</td>
<td>225 kV</td>
</tr>
<tr>
<td>green setup</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>blue setup</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>red setup</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.3: Capacitors present in substations 1 and 2

<table>
<thead>
<tr>
<th></th>
<th>Substation 1</th>
<th>Substation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400 kV</td>
<td>225 kV</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The double line tripping (see section 5.2.1) is now simulated and the result for each setup is plotted in figure 5.10. The curves represent the voltages at substation 1 on the 400 kV level. We can notice that only the simulation with the blue setup manages to converge.

The switching events of the capacitors are represented in the tables 5.4 and 5.5 for the three setups.

Regarding the simulation with the red setup, the peak of voltage after the fault leads to a disconnection of two capacitors as shown in figure 5.11 by the SMACC 1 (SMACC present in substation 1) and then the system collapses very quickly. However it seems more complicated to explain why the simulation with the green setup collapses and not the simulation with the blue setup. In fact we cannot explain this result by a lack of capacitors, as we did with the red setup, since the green setup has during the simulation the most capacitors connected compared to the other setups.
In order to highlight the differences between the simulations with the green and the blue setups, some parameters have been studied such as the on-load tap changers and the units production. It turned out that the voltage collapses of the green setup is caused by a delay of the blocking tap changers. The figure 5.12 represents the tap changers in five areas. When the voltage becomes low, the OLTC has to stop to change their tap positions in order to limit the demand as seen in section 3.3.3. The variable plotted in the figure 5.12 represent the state of the OLTC and when this variable goes down to $-1$, it means that the OLTC is blocked and we can see in the figure that the on-load tap changers of the green setup are blocked later than the ones of the blue setup and this leads to a voltage collapse. We can explain this phenomenon by the connection of a capacitor 400 during the simulation with the green setup at $t = 576s$ (see table 5.5). As a matter of fact, this connection makes the voltage map be higher and as a result, the blocking of the on-load tap changers is delayed.
In order to validate this hypothesis, the simulation with the green setup is performed again but the capacitor 400 is now connected manually. The switching time to connect manually the capacitor is chosen as the same than for the blue setup with the capacitor 225 at $t = 591\, \text{s}$ (see table 5.5). The new results are plotted in dark blue in figure 5.13 and the result of the original green setup is still plotted in order to compare both simulations. It can be seen that now the green variant with manual switching manages to stabilize.

From this first simulation it is possible to draw some conclusions about the setup of the SMACCs. In fact the simultaneous disconnection of capacitors in the case of the red setup led very quickly to a voltage collapse. Then the quick connection of a capacitor in the case of the simulation with the green setup also led to a voltage collapse. Consequently, the parameters of both SMACC 1 and SMACC 2 have to be defined accordingly to avoid those phenomena.
CHAPTER 5. TEST OF THE SMACCS

Simulation 2: Simulation with the HVDC line between France and Spain  For this second simulation, the HVDC line has been included in the network. Today only the conversion stations at both the extremities of the line are used and consequently the HVDC line can only produce or absorb reactive power. Both conversion stations can produce or absorb 300 MVar. For the simulation, the HVDC line between France and Spain has been modelled such as the active export are limited at 50 MW (2000 MW in reality). The situation studied is exactly the same as the simulation 1 57. Then, only one setup is tested in the simulation with all the capacitors connected initially as shown on table 5.6.

<table>
<thead>
<tr>
<th>Setup</th>
<th>Substation 1</th>
<th>Substation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400 kV</td>
<td>225 kV</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.6: Setup studied

The results of the simulation without the HVDC line are plotted in blue and the one with the HVDC line is plotted in green. As shown in figure 5.14, the simulation without the HVDC line leads to a voltage collapse whereas the simulation with the HVDC line manages to stabilize at $t = 700s$. The switching events of capacitors are the same for both cases as shown in table 5.7. It can be seen that the disconnection of capacitors only happen in substation 1, where the peak of voltage is the most important.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Without HVDC</th>
<th>With HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>524</td>
<td>Disconnection 225</td>
<td>Disconnection 225</td>
</tr>
<tr>
<td>526</td>
<td>Disconnection 400</td>
<td>Disconnection 400</td>
</tr>
</tbody>
</table>

Table 5.7: Substation 1: Capacitors switching events
We can also notice that the peak of voltage due to the fault is lower with the HVDC line as shown in figure 5.15. However, this is not sufficient to avoid the disconnection of capacitors. The peak of voltage is actually mitigated by the conversion stations of the HVDC line which absorbs the excess of reactive power. The goal of the HVDC line is to maintain the voltage values of its extremities to a setpoint value. The figure 5.16 represents the voltage at the french extremity of the line for both simulations and we can notice that the green curve (simulation with the HVDC line) manages almost to remain constant and equal to the voltage setpoint of the conversion station.
5.3 Conclusion

The integration of the SMACC depends on a large range of parameters. After a disturbance, the reactive power production of the generators may be quickly limited by the secondary voltage control. This can have the bad effect to lead to a voltage collapse if the generators cannot supply enough reactive power.

A quick connection of capacitors after a fault may delay the sending orders of the blocking tap changers into certain areas and then lead to a voltage collapse. A quick connection of capacitor can also make another one disconnect due to an exceeding of the voltage threshold. It is then necessary to wait 5 minutes before that the disconnected capacitors be connected again and this is not optimal for the system stability.

The integration of the HVDC line is really beneficial for the system stability. The HVDC lines enables in certain circumstances to mitigate the peaks of voltage (and so the eventual capacitor disconnection), and the conversion stations can also supply 600 MVar to the system which enables to maintain a constant voltage map or at least to maintain the voltage map above critical values. Finally, to improve considerably the performance of the SMACCs, their operating diagram should take into account more data such as the reactive exports through sensitive lines. As a result, we could forbid the connection of capacitors if the exports exceed a given limit in order to avoid a peak of voltage after a disturbance.
Chapter 6

Setting up of an Under Voltage Load Shedding (UVLS)

6.1 Context and Methodology

With the increasing of electricity consumption it has been highlighted recently that there is a potential risk of voltage collapse in the South-West of France after very severe contingencies and in case of heavy loads. The risks of voltage collapse are studied on diverse backgrounds and are taken into account in the setting up of various operating rules to protect themselves against some usual or normal problems, as we seen with the $N-1$ rule, in section 3.4.1. However, it may happen that the South-West network cannot always covered against particular $N-2$ defaults and if this happens, it is necessary to act as quick as possible to avoid that a voltage collapse spreads on a large scale. The role of the under-voltage load shedding is to cut some consumers from the network in the area where the fault happens. In fact it is preferable to loose several consumers rather than the whole population connected to the grid.

A forecasting reference situation of 2019 is the main support for the simulations in both Convergence and Eurostag. First this situation is studied in order to evaluate if a load shedding device is necessary. Various parameters which have an impact on voltage stability are studied and the original situation (2019) is calibrated in order to have more stress than initially. Since this situation is a forecasting situation, it is better to try the load shedding on a network with more constraints than expected. In parallel, all defaults which can lead to a voltage collapse are simulated. Then after the modelling of the load shedding device, different setups of LSD are studied in Convergence and Eurostag.

6.2 Voltage Stability study in South-West of France

6.2.1 Situation studied

The network situation on which we will make all our simulations is a 2019 forecasting situation in case of heavy loads such as the one in winter. In this situation the HVDC line is also taken into account and will be discussed more in details in the section 6.2.2. Moreover, the SMACCs
are not included the simulation. In fact, since a stressed situation is needed for the simulation to try the load shedding setups, all capacitors are supposed to be connected initially since the low voltage map before the default. Then, the defaults studied always lead to a voltage collapse and as a result, the capacitors have to remain connected during the simulation. Even if the SMACC had been used in the simulations, it wouldn’t have disconnected capacitors and the results would have been the same.

6.2.2 HVDC line

In this study we also introduce the HVDC lines between France and Spain. The maximum active power transfer is 2000 MW and its capacity of reactive absorption or supply are 600 MVar on each side of the line. The second HVDC lines in South of France is not taken into account. The technology of the HVDC is the Voltage-Sourced Converters. This technology (compared to the Line-Commutated Converters) has the advantage to use IGBT transistors which can be turned on and off. This enables the system to get one more degree of freedom and so to control both active and reactive powers.

For each simulation, different variants are tested by varying the export between France and Spain. For a given quantity of export/import, the active flows through the HVDC line are adapted in order to remain coherent with the other export. For example if the AC line next to the HVDC line is sending 500 MW to France, then the HVDC line is configured to send also power to France. In reality, the line is not supposed to be controlled as an AC line (the power flows through DC line are the same as if this line was an AC line) but it will be adapted manually by the operator. This is exactly the second option that is used for the simulation. The HDVC is firstly adjusted manually before the fault in order to get power flows in the right direction and at a good level.
6.2.3 LSD model in Convergence and Eurostag

The figure 6.1 represents the structure of the load shedding device for the simulations. Before using the LSD, a set of loads to be shed has to be chosen first. In fact, when a load shedding order is sent by the device, all the loads present in a given load area are shed. As shown in figure 6.2, the South-West region of France is divided into six load areas.

The figure 6.1 represents the structure of the load shedding device for the simulations. Before using the LSD, a set of loads to be shed has to be chosen first. In fact, when a load shedding order is sent by the device, all the loads present in a given load area are shed. As shown in figure 6.2, the South-West region of France is divided into six load areas.

Then the monitoring node has to be chosen accordingly in the load area that has to be shed. Thus if the monitoring node voltage falls below a given voltage threshold (which has to be defined first), then the LSD gives the order to shed loads. Finally the percentage of load to be shed lies between 10% and 20% for each step. In that way, 60% is the maximal percentage of load that can be shed as a part of load has to be continuously maintained (as an uninterrupted load).
6.2.4 Simulations on Convergence

Parameters influence

The main goal of this part is to emphasize the parameters that can have an impact on the voltage stability. The studied parameters are the export between France and Spain (and indirectly the Spanish consumption), the generators reactive limitations, the $\tan \phi$ and the French consumption. Then two defaults, which are the most severe regarding the system stability, are tested and the drop of voltage in a given node $X$ after default is expressed in $kV$. The node $X$ is chosen in order to be sufficiently representative of all the nodes of the South-West region. Then both defaults respectively lead to a double line tripping and a double generator tripping.

We are first dealing with the impact of the exports between France and Spain. The double line tripping and the generators tripping are simulated for five different setups of export (from France to Spain). We can notice in figure 6.3 that the exports have a big impact on voltage stability particularly when France exports more than 1000 MW to Spain. The red star in the figure represent a voltage collapse. The double line tripping seems to be the most severe default and we can even point out that the system collapses with an export of 1117 MW.

![Figure 6.3: Variation of the exports France-Spain](image)

The reactive limitations of some generators are studied in a second part (The generators which are disconnected for the default "generators tripping" are not limited). It can be seen in figure 6.4 that the most the generators are limited and the most important is the drop of voltage after the defaults. This result was expected because if a generator cannot produce enough reactive power, then it is necessary to import reactive power from the neighbouring areas which leads to important voltage drop. On the figure it is possible to notice that the default which is the most sensitive to the reactive limitations is the generators tripping even if it doesn’t lead to a voltage collapse.

We are now focusing on the consumption in the South-West of France. As shown in figure 6.5, the consumption has an important impact on the system stability. We can notice that the double line tripping (respectively the generators tripping) default leads to a voltage collapse (red stars) when the stress of consumption is higher than 1400 MW (respectively 2000 MW).
Finally, the impact of the \( \tan \phi \) of the load is studied. For a given active load, an increasing of the \( \tan \phi \) means an increasing of the reactive loads and if the reactive loads increases, more reactive power has to travel which can induce drops of voltage. The initial \( \tan \phi \) from the initial forecasting situation is actually very low and cannot fit with the stability studies. By increasing the value of the \( \tan \phi \), it can be seen in figure 6.6 that the drop of voltage after both defaults increases when the \( \tan \phi \) is getting higher.

After these different studies, the initial situation can be calibrated by increasing the export France/Spain, the \( \tan \phi \) and the South-West consumption and by decreasing slightly the reactive limitations of some units. As a result the situation is more stressed and this is preferable to define properly the parameters of the LSD. In fact, if we find an efficient load shedding setup with the situation under study, the same setup will be efficient on the forecasting situation since it is supposed to be less stressed.
CHAPTER 6. SETTING UP OF AN UNDER VOLTAGE LOAD SHEDDING (UVLS)

Figure 6.6: Variation of the $\tan \phi$

Load shedding in Convergence

The simulations in Convergence aim to find the suitable loads areas (as seen in section 6.2.3) to be shed during a phase of voltage collapse. The forecasting situation is now calibrated and the default used to create voltage collapses in the double line tripping (section 6.2.4) since it appears to be the most severe default. Then during the phases of voltage collapses different setups of load shedding are tested to see which ones respond the best as possible. Since there are six load areas, for each voltage collapse six setups are tested.

Figure 6.7: Load shedding after a double line tripping

For each simulation, the best load shedding is selected as the one capable of avoiding the voltage collapse by shedding the less load as possible. In figure 6.7, a voltage collapse and the response of one setup of load shedding is represented. The load shedding device has shed the load 3 times (30% in whole). At the end of this study three load shedding setups are selected for the simulations in Eurostag.
6.2.5 Simulations on Eurostag

Three load shedding setups are studied in Eurostag. One setup corresponds in fact to a load shedding in a given area. For simplicity, we will call them green, blue and red load areas. To ensure the RTE confidentiality, the colors given above to the load areas doesn’t respect the colors given in section 6.2.3. Besides, the same default (double line tripping) is used for the simulation.

Simulation 1: HVDC fully loaded

Before the default, the HVDC line is fully loaded (2000 MW) and the support for the simulations is still the calibrated forecasting situation (2019). The total active power export from France to Spain (both AC and DC lines) reaches 2815 MW.

As shown in figure 6.8, the default simulated in Convergence leads also to a voltage collapse in Eurostag, mainly caused by a cascading loss of generating units due to their low voltage protection. It is then possible to try the three load shedding setups.
SETTING UP OF AN UNDER VOLTAGE LOAD SHEDDING (UVLS)

Figure 6.9: Load shedding in the green load area

Table 6.1: Green load area: Load shedding events

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2602</td>
<td>17 % - 1000 MW</td>
</tr>
</tbody>
</table>

Setup 1: load shedding of the green load area  The load shedding threshold is set at 345 kV and the percentage of load to be shed at each step is equal to 17%. It can be seen in figure 6.9 and table 6.1 that only one load shedding of the green area is necessary to avoid the voltage collapse. The curves plotted at the top of figure 6.9 represent in fact the voltages of the monitoring nodes of each load area (except the purple curve). For example the green curve represent the voltage of the monitoring node of the green area. The bottom of figure 6.9 represents the sending order of load shedding.
Setup 2: load shedding of the blue load area  In this case, three load sheddings are necessary to relieve the system and then avoid the voltage collapse as shown in figure 6.10 and table 6.2. Then we can point out that the percentages of load shedding are not the same depending on the moment of the load shedding. In fact the load shedding is made from the remaining load and since we want to shed the same amount of load at each step, it is necessary to compensate the load which has already been shed by increasing the percentage for the next load shedding.
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Figure 6.11: Load shedding in the red load area

Table 6.3: Red load area: Load shedding events

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2580</td>
<td>17 % - 600 MW</td>
</tr>
<tr>
<td>2597</td>
<td>20 % - 600 MW</td>
</tr>
<tr>
<td>2612</td>
<td>26 % - 600 MW</td>
</tr>
</tbody>
</table>

Setup 3: load shedding of the red load area  As with the blue area, it can be seen in figure 6.11 and table 6.3 that three load sheddings of the red area are necessary to maintain the system stability and this represents more than 1700 MW. To conclude this first simulation, it appears that the green load area is the most appropriate area for the load shedding since only one step is necessary to avoid the voltage collapse. This can be explain by the fact that the green area represents 20% of the total load of the South-West region. Then the default simulated (double line tripping) is located inside the green area which means that by load shedding the green area, it is possible to act very close to the disturbance.
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Simulation 2 : HVDC half loaded

In this simulation the HVDC line is half loaded (2 * 500 MW) before the default and the power exports from France to Spain equals 2535 MW (instead of 2815 MW in the first simulation). In fact the spanish consumption is decreased to make the situation less stressed. As for the simulation on Convergence, the reactive power production of several generators is limited. We can notice in figure 6.12 that the default still leads to a voltage collapse.

Contrary to simulation 1, it can be seen that the voltage collapse happens 75 seconds after the default (65 seconds in simulation 1). This can be explained by the initial state of the current situation which is less stressed than the one in simulation 1. The three setups of load shedding described in simulation 1 are now tested for simulation 2.
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Figure 6.13: Load shedding in the green area

Setup 1: load shedding of the green load area  Contrary to simulation 1, the load shedding of the green area doesn’t avoid the voltage collapse as shown in figure 6.13. The cascading loss of generators happens before that the LSD starts shedding loads. In fact since the situation is less stressed, the monitoring node voltage of the green area is always higher than the load shedding threshold before the collapse. As a result, the load shedding threshold is increased by 5 kV to make the device able to shed load before the cascading loss of power units.
CHAPTER 6. SETTING UP OF AN UNDER VOLTAGE LOAD SHEDDING (UVLS)

Figure 6.14: Load shedding in the green area with a higher threshold value

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2610</td>
<td>17% - 1000 MW</td>
</tr>
</tbody>
</table>

Table 6.4: Green load area: Load shedding events

**Setup 1: load shedding of the green load area** The load shedding threshold is increased to 350 kV and it can be seen in figure 6.14 and table 6.4 that the LSD manages to shed 17% of load. However the load shedding setup doesn’t prevent the voltage collapse after the double line tripping. In fact it can be seen that the voltage in the red area remains very low despite the load shedding. Then, by imposing a lower active power flows through the HVDC line (which is located on the east side of the cross-border) before the default, the active power flows are consequently increased on the west side of the border and through the AC lines which lead to a voltage decrease of severale nodes. After the default and despite the load shedding of the green area, several generators, especially on the west area, still have low statoric voltages. As a result, these power units are disconnected (due to the low voltage protection) and the voltage collapse is going on.
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Figure 6.15: Load shedding in the blue area

Table 6.5: Blue load area: Load shedding events

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2595</td>
<td>17 % - 400 MW</td>
</tr>
<tr>
<td>2611</td>
<td>20 % - 400 MW</td>
</tr>
</tbody>
</table>

Setup 2: load shedding of the blue load area  The load shedding of the blue load area is still efficient as shown in figure 6.15 and table 6.5, and the voltage collapse is avoided by two load sheddings, contrary to simulation 1 where 3 load shedding are done due to the more stressed initial situation. However it can be seen that the voltage value of the red node (which is the monitoring node of the red area) is still very low and some power units are close to disconnect.
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Figure 6.16: Load shedding in the red area

Table 6.6: Red load area: Load shedding events

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2576</td>
<td>17 % - 600 MW</td>
</tr>
<tr>
<td>2591</td>
<td>20 % - 600 MW</td>
</tr>
<tr>
<td>2607</td>
<td>26 % - 600 MW</td>
</tr>
</tbody>
</table>

Setup 3: load shedding of the red load area  The load shedding of the red area is exactly the same as the one in simulation 1 (with the HVDC line fully loaded). It can be seen in figure 6.16 and table 6.6 that three steps are necessary to stabilize the system and more than 1700 MW are shed. Therefore, compared to load shedding in the blue area, more loads are shed to avoid the voltage collapse. However the nodes voltages in some part of the network are still very low in the case of the load shedding in the blue area, and this can induce low statoric voltage for some generators.

Compared to simulation 1, the decreasing of the power flows from the HVDC lines increases
the voltage values of the node close to the line (before the default). This is the reason that explains why the voltage values of the nodes in the green or the blue area are high (compared to the nodes in the red area which is located far from the HVDC line) and why there are only few load shedding during the phase of voltage collapse. However, by decreasing the power flows through the DC line, the red area is weakened before the default due to the increasing of power flows, and the only load shedding that can avoid efficiently the collapse has to be made in the red area as it is shown in figure 6.16.

It can be conclude from simulation 1 and simulation 2 that depending on the initial conditions (power flows through the HVDC line, consumption in Spain or in France), and for a same default (in our the case the double line tripping), it is very difficult to have only one load shedding setup. The load shedding in the red area is the only one that can stabilize efficiently the system in simulation 2, but the same load shedding in the case of simulation 1 is almost excessive since too much load is shed. To take benefit from the load shedding in both red and blue areas, a combination of LSD setups is tested as it is shown in figure 6.17 and table 6.7.

![Figure 6.17: Load shedding in the blue and red load areas](image)

| Voltage threshold (red area) | 345 kV |
| Voltage threshold (blue area) | 350 kV |

For the combination of load shedding, the same nodes are monitored and only the voltage threshold on the LSD in the blue area is increased, to avoid a unique load shedding in the red area. By combining load shedding setups in both blue and red areas, it is possible to monitor
CHAPTER 6. SETTING UP OF AN
UNDER VOLTAGE LOAD SHEDDING (UVLS)

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Load shedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>2576</td>
<td>blue area : 17% - 400 MW</td>
</tr>
<tr>
<td>2612</td>
<td>red area : 17% - 600 MW</td>
</tr>
<tr>
<td>2628</td>
<td>blue area : 20% - 400 MW</td>
</tr>
</tbody>
</table>

Table 6.7: Load shedding events

A broad zone and therefore to anticipate a voltage collapse at different places. The voltage collapse in this case is avoided and the system recovery is better than with the other setups. However it is not possible to conclude if this is the optimal solution or not. For instance, the system can maybe avoid the voltage collapse without the last load shedding in the blue area at $t = 2628s$ and perhaps a load shedding of 1000 MW may be enough.

6.3 Conclusion

It is shown that the location where the voltage collapse starts is highly dependent on the exchanges through the interconnexion lines between France and Spain, as well as other parameters such as the consumption in Spain or in France. As a result it seems preferable for the system stability that, if a load shedding is necessary, to install the LSD in several areas in order to avoid the voltage collapse whatever the locations of the defaults and the initial state of the network.

A particular attention should be carried on the areas where we can find several power units. If a LSD takes too much time before shedding the load, there is a high risk to make those units trigger due to the low voltage criterion. Finally we noticed during the study that the voltage values in the South-West of France are very similar during the collapsing phase and consequently we could also imagine a LSD set up in several areas that will shed load if a given number of voltage values go down a critical limit.

Ultimately, the forecasting situation of 2019 has been severely stressed for the simulations since the initial situation couldn’t lead to a voltage collapse after severe defaults (even $N - 2$ default). In that way the spanish consumption has been increased in order to get power flows from France to Spain (which is usually not the case in winter). As a result, instead of installing LSD in the South-West region, another strategy could be to give special attention on the exports from France to Spain and thus limit the flows to a given limit.
Bibliography


