KTH Electrical Engineering

Master's thesis report

Static security criteria for voltage stability assessment in the French transmission grid

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ABSTRACT

As the electric consumption increases and the investments are hard to make, electricity networks are operated closer to their limits. In such conditions, a generator or a transmission line outage can have tremendous impact, leaving a great number of people without electricity. It is therefore a matter of prime importance to ensure power system security and in particular voltage stability. Static criteria used in on-line simulations as well as protection and defense devices such as load-shedding devices play a critical role for voltage stability and are thus crucial for the network security. The core of this project is to determine efficient tools to detect undesirable conditions in operational context and to determine a pertinent activation level for an automatic load-shedding device used for the system protection against voltage instability.

In the first part of this report, theoretical background regarding voltage stability is presented, followed by the software and methodologies used during the Master's thesis work.

The second part of this report focuses on case studies conducted for the French power system. From an initial objective of updating static criteria, the results have actually led to the withdrawal of these criteria and a switch to dynamic simulations for the North-East and East areas, as well as to the improvement of Astre software database. Simulations on the most stressed conditions from last winter allowed the updating of the activation level for the automatic load-shedding device. These changes have been validated and will be applied for voltage security assessment of the French network in the future.

ACKNOWLEDGEMENTS

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I'm thankful to my girlfriend Alexandra for her constant support and love, either in Sweden or in France, and for her patient rereading and help on this report. As this report will certainly be the last of my student's life, my final thanks will go to my family – to my parents for everything they have taught me and for their constant support and to my brother who has been a perfect example for me.

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ABBREVIATIONS AND EXPRESSIONS

CNES : *Centre National d'Exploitation du Système* – National Center for System Exploitation

DES: *Département Exploitation et Systèmes* - Exploitation and System Division

EDF : *Electricité de France* – French main electricity producer

EHV: Extra High Voltage

ERDF : *Electricité Réseau Distribution de France* – French main ditribution operator

GDF: *Gaz de France* – French electricity producer

GPM: *Gestion Prévisionnelle et Maintenance* – Previsional Handling and Maintenance

HV: High Voltage

LSD: Load-Shedding Device

LTC: Load-Tap Changer

QSS: Quasi Steady-State

RTE: *Réseau de Transport d'Electricité* – French transmission operator

SLIB: Single-Line Infinite Bus

TSO: Transmission System Operator

In this report, margin calculation and margin computation have been used interchangeably. Fault, disturbance and contingency have also been used interchangeably. On-line studies refer to studies done in operational contexts and the expression off-line studies has been used to refer to studies done in prospective, research or analysis context.

1 INTRODUCTION

1.1 PRESENTATION OF RTE

RTE (*Réseau de Transport de l'Electricité*) is the French Transmission System Operator (TSO) and thus is responsible for the transmission system linking generating units to load areas. Indeed, the structure of an electric power system can be summarized in the following way: generators produce electricity that is fed into the system and delivered to load centers through transmission lines (Figure 1.1).

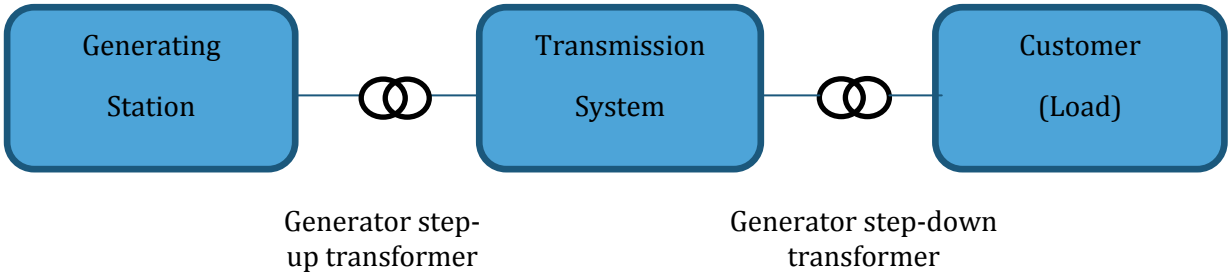


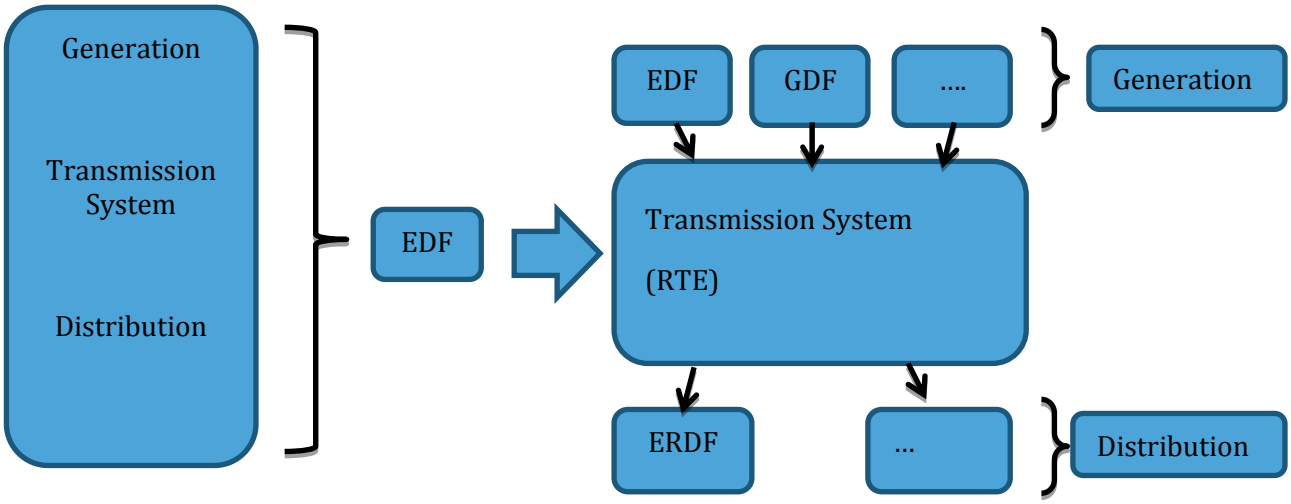
Figure 1.1 *Structure of an electric system* ***[10]***

RTE was created on July the 1st, 2000 as a result of European Directive No. 96/92/EC which became a French law in February 2000 [1]. The directive required France to liberalize its electricity market by separating the generation from the transmission activities, thus bringing to an end the vertically integrated organization of the French power system (see Figure 1.2). RTE has a public mission: guarantee equitable access to electricity, and ensure the continuity and quality of electricity supply.

Additional legal acts in 2005 enforced the legal separation of RTE and EDF (*Electricité de France* – the French main producer of electricity). RTE became a limited liability subsidiary of EDF whose activities are overseen by the Government regulatory body *Commission de Régulation de l'Energie* (Commission for Energy Regulation – CRE). Now RTE is in charge of more than 100 000 kms of high-voltage (HV) and extra-high voltage (EHV) lines, employs more than 8.000 people, for a revenue of four billion euros [2].

In order to fulfill its public mission, RTE must:

- maintain balance between consumption and production
- guarantee the security of the electric system, that is to avoid local or global blackouts
- guarantee a good quality of electricity - satisfactory voltage and frequency levels for the users
- develop the network and make it more secure by adapting its investments to the load and its evolution
- contribute to a smooth functioning of the electricity market



ERDF = *Electricité Réseau Distribution de France* (main French distribution operator)
GDF = *Gaz de France* (a French power producer)

Figure 1.2 *Liberalization of the electric power system activities in France*

To achieve these goals, RTE has adopted the following organization: regarding exploitation issues, the French grid is divided into seven areas with an operational center in each area and a centralized operational center called CNES (Centre National d'Exploitation du Système – National Center for System Operation) located near Paris (see Figure 1.3). RTE has a lot of other divisions and employees: service engineers, up keeping and installation teams or financial and trading units for example.

This Master's thesis work has been done in DES (*Département Exploitation et Systèmes* – Exploitation and System Department) in Versailles, which is a part of the R&D unit. DES department is divided into five different working groups. It leads studies on various subjects, ranging from European projects for the 2050 network to the development of tools to maintain the equilibrium between production and consumption by running quasi real-time simulations[1], or to an evaluation of the impact of renewable energies on the French grid. There are around 80 people working in this department. I was a member of the group GPM (*Gestion Prévisionnelle et Maintenance* – Previsional Handling and Maintenance), my supervisor's group, and worked mainly on voltage stability issues.

[1] Quasi-real time simulation refers to half-an-hour ahead simulation.
[2] A system state is characterized at an instant by the consumption level, the generating units available and

Figure 1.3 *Areas of the French network* ***[3]***

Nord-Est: North-East ; *Est:* East ; *Sud-Est :* South-East ; *Ouest :*West ; *Sud-Ouest :*South West

1.2 CONTEXT EVOLUTION AND CHALLENGES FOR TSO

Over the past few years, the electricity sector context has undergone many changes: the development of renewable energies, the continuous increase of consumption, the liberalization of the electricity market, etc. In this section, the resulting challenges for the TSOs will be presented.

Environmental issues and global warming are nowadays worrisome issues for most of the people in the world and have led governments to take measures in order to find and develop new sources of energies: renewable energies. For example, European Union members have agreed to decrease their emissions levels by 20% in 2020 compared to their 1990 levels, mainly by decreasing the energy consumption by 20% by this date (thanks to energy efficiency measures) and by increasing the part of renewable energies up to 20% of the energy mix [4]. In order to face the challenge of a more eco-friendly energy, governments have given incentives to increase the part of renewable energies in the mix. Depending on the countries, measures such as constant and interesting price guaranteed for renewable sources, grants for the installation of photovoltaic or wind power plants or minimum part of production coming from renewable sources for the producers have been voted.

The impact of these different measures is shown on the following figures (Figure 1.4 and Figure 1.5).

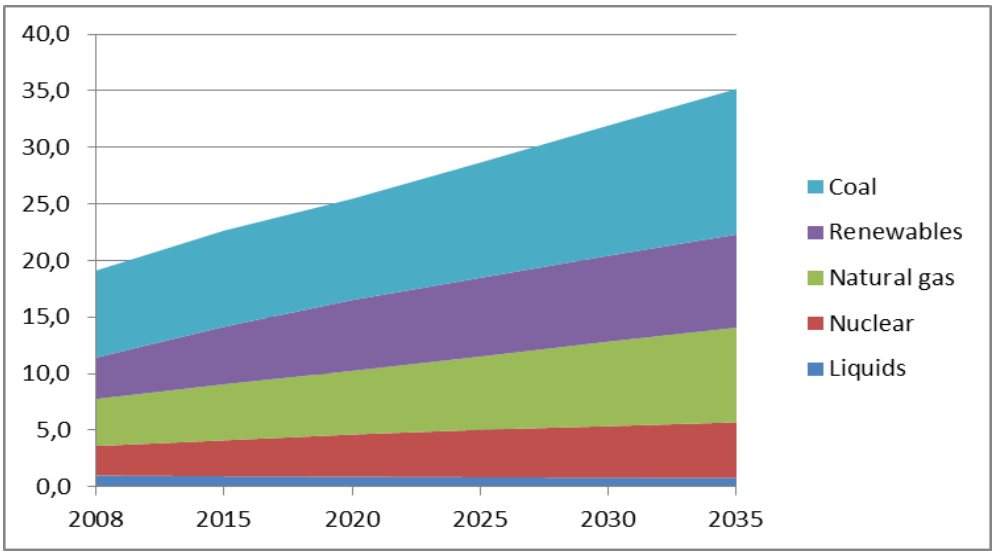


Figure 1.4 *Evolution of the world net electricity generation by fuel in trillion kilowatthours* ***[5]***

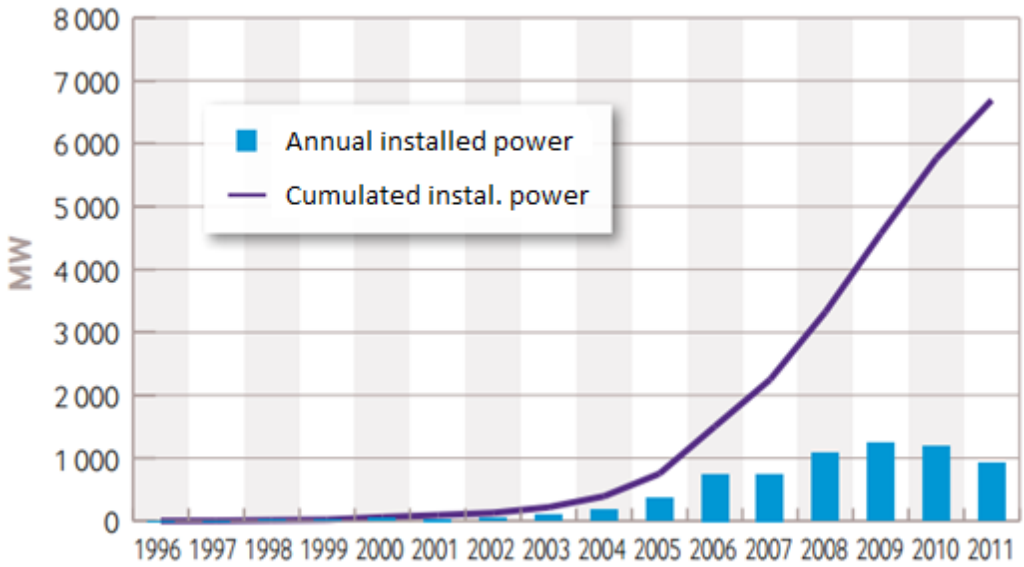


Figure 1.5 *Evolution of the wind power potential in France* ***[6]***

This increase of the share of electricity produced by renewable sources is a challenge for the TSOs. Indeed, production from these units is difficult to predict (for example, in the case of wind power, the production depends on wind speed – see Figure 1.6). Moreover, some questions are still under discussion regarding this development. For instance, if we imagine a network with a high rate of penetration of renewable energies, in case of an emergency situation, how could TSOs keep an acceptable voltage level or an acceptable frequency if they can't adjust the productions (both for active and reactive power)? What is the behavior of these power plants in case of a disturbance on the network?

Renewable energy production has been increased in many countries over the past few years, and this growth is expected to continue in the next years. TSOs have gained more experience in

these new technologies and learned their effect on the network but there remain many issues to study in order to completely overcome this challenge.

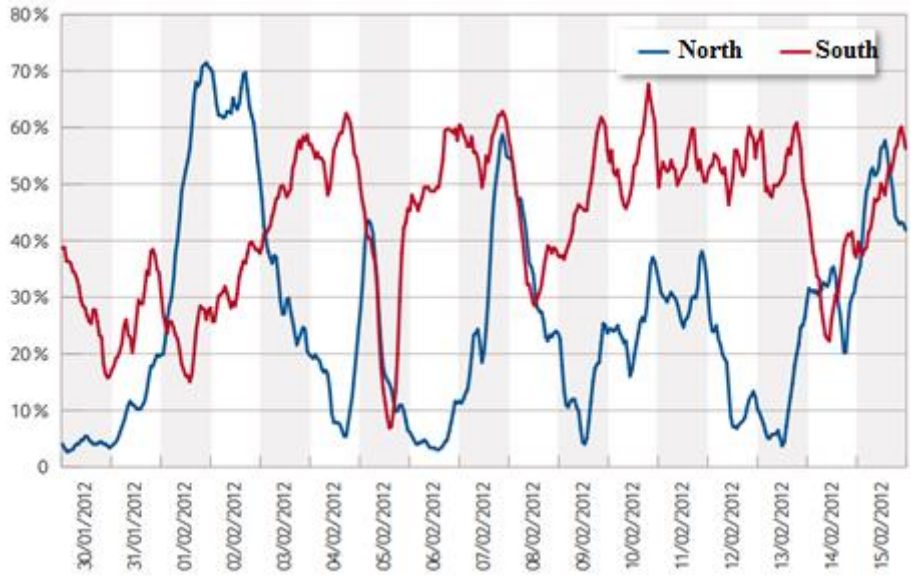


Figure 1.6 *Participation factor for French wind power plants during the peak consumption from last winter* ***[6]***

Another challenge for the TSOs is the constant load increase (Figure 1.7). Indeed, the consumption increases faster than the investments in new power plants. As a consequence, existing power plants are operated closer to their limits. In these conditions, an outage can have tremendous impact. Moreover, as it is difficult to invest in power plants as well as in transmission lines (nobody is willing to welcome a nuclear or a coal plant close to their home, and the same goes for an EHV transmission line), the existing power lines are heavily stressed. The Fukushima accident also led to major changes in the European network with the decisions of Germany and Belgium to stop all their nuclear units in the near future. (2022 [7] and 2025 [8] respectively).

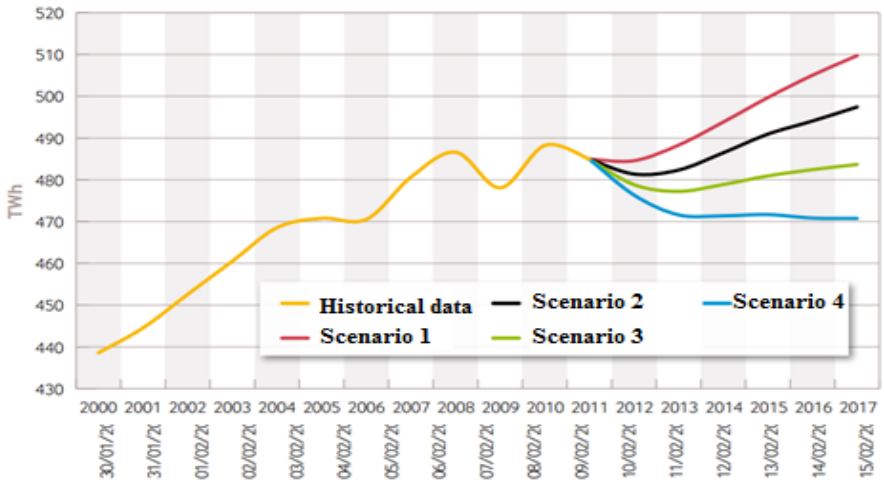


Figure 1.7 *French consumption evolution from 2000 to 2017* ***[6]***

Another major change is the liberalization of the electricity market. Many countries such as France and most European countries have moved from vertically integrated power electric companies to a structure where production and distribution are opened to competition and only transmission remains a monopoly. With this new structure, it has been a necessity to organize for example the money compensations for power units that can adapt their active or reactive productions in order to keep an acceptable frequency on the network or an acceptable voltage level. Indeed the frequency or voltage levels are under the responsibility of the TSOs but the units are owned by the power producers. It is also nearly impossible for TSOs to install sensors on the power plants in order to better tune the regulators used in the models for instance.

The last challenge that will be mentioned is the growing importance of power transfer between countries. The networks of neighboring countries are linked together by existing AC and DC lines, and new ones are under construction or at least in project (for France for example, we can mention the HVDC existing line between France and England and another under construction between France and Spain). It is thus an issue of prime importance for TSOs to understand how the neighboring countries networks are operated by the other TSOs. A disturbance caused by a problem in Germany for example or in Spain will impact all Europe.
European countries are aware of this issue and try to address it with more cooperation between TSOs but this task is really difficult due to the difference of technical habits or the difference in grid codes between the countries. For example, Switzerland, which is a country with high export and import power passing through its borders, may decrease the import and export power in some operating conditions which will lead to power shortage in the North of Italy.

In conclusion, TSOs, which were created after the liberalization of electricity market, are young entities which are operating in a changing environment with multiple but exciting challenges:

- Adapt their methods and networks to the development of renewable energies
- Guarantee the electricity supply despite the consumption increase and the difficulties to build new infrastructures
- Increase and improve the cooperation between TSOs from different countries to face global issues.

1.3 POWER SYSTEMS STABILITY

We have seen that TSOs have many challenges to handle, and since modern society is strongly dependent on electricity, high reliability of supply and high level of system security are of fundamental importance. Moreover, power systems are frequently subject to various types of disturbance but must be able to adjust to these changing conditions and to operate in a satisfactory way whatever the conditions. System security is the main goal for a TSO.

Power system stability is crucial for system security and is defined by IEEE/CIGRE Joint Task Force in the following way:

"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"[9] .

In order to facilitate the analysis of stability, power system stability has been classified into different categories (Table 1.1). Separation has been done by considering driving force and time scale criteria in [10], [11] and [12]:

Time-scale	*Generator-driven*	*Load-driven*
Short-term	Rotor angle stability	Short-term voltage stability
	Small-Signal, Transient	
Long-term	Frequency stability	Long-term voltage stability
		Small disturbance, Large disturbance

Table 1.1 *Power System Stability Classification* ***[11]***

Rotor angle stability refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after a disturbance. Instability that can result occurs in the form of increasing of angular swings of some generators leading to their loss of synchronism with other generators. Loss of synchronism can occur between one machine and the rest of the system or between groups of machines, with synchronism maintained within each group ([10], [11] and [12]).

Rotor angle stability can be divided into:

- Small-signal stability concerned with the ability of the power system to maintain synchronism under small disturbances. In these conditions, linearization of system equations is possible.
- Transient stability is for large disturbance, such as short-circuit on a transmission line and depends on the initial operating conditions of the system as well as the characteristics of the disturbance (location, severity and type).

Frequency stability is the stability in long-time scale for generator-driven stability. It is the ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load [10].

Short-term voltage stability is characterized by components such as induction motors, excitation of synchronous generators and electronically controlled devices such as HVDC and Static VAR Compensator. The time-scale of short-term voltage stability is the same as the time-scale of rotor angle stability: the dynamics typically last a few seconds ([11] and [12]).

Long-term voltage stability, which will be the main topic of this Master's thesis, lasts for tens of seconds to minutes. It refers to the ability of the system to maintain steady voltages at all buses after being subjected to a disturbance from a given initial operating condition. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses ([10], [11] and [12]).

An important principle regarding power system security is the so called N-1 criterion. The N-1 criterion states that the power system must be operated at all times such that after an unplanned loss of an important generator or transmission line it will remain in a secure state. Furthermore, when a loss occurs the system must be returned to a new N-1 secure state within a specified time (normally within 15-20 minutes) to withstand a possible new loss [10].

However, despite all the precautions taken by TSOs to limit the consequences of the different disturbances and to assure the security of the system – that is satisfying at least the (N-1) criterion -, there have been some major problems during the last fifty years. We will focus on

two major incidents: the incident on the French grid in 1987 and the Switzerland-Italy problem in 2003. The 1987 voltage decrease in France was initiated by the losses of two generators of the coal production unit named Cordemais in less than one hour. The temperature was very low (around -13° C this day) and the consumption very high so all the available generators were operating. Ten minutes later after the second unit, a third generator was then disconnected at Cordemais for a third unrelated reason. After this loss, fifteen seconds later, the last generator of Cordemais was also disconnected from the network due to low voltage values at its connecting point. These different losses led to a huge voltage level decrease and the problem spread to surrounding areas. In these areas, some other generators were disconnected and other couldn't increase their reactive power production in order to respect their rotor current limit. At this point, situation was really critical on some parts of the French network and protection actions were taken -consumption load-shedding, on-load tap changer blocking, etc. -. Thanks to these actions, the system collapse was stopped and after some other operations, it was possible to restore the pre-fault condition. The events presented here are described in a RTE internal note that can't be given in the references but the information provided can be found on the Internet.

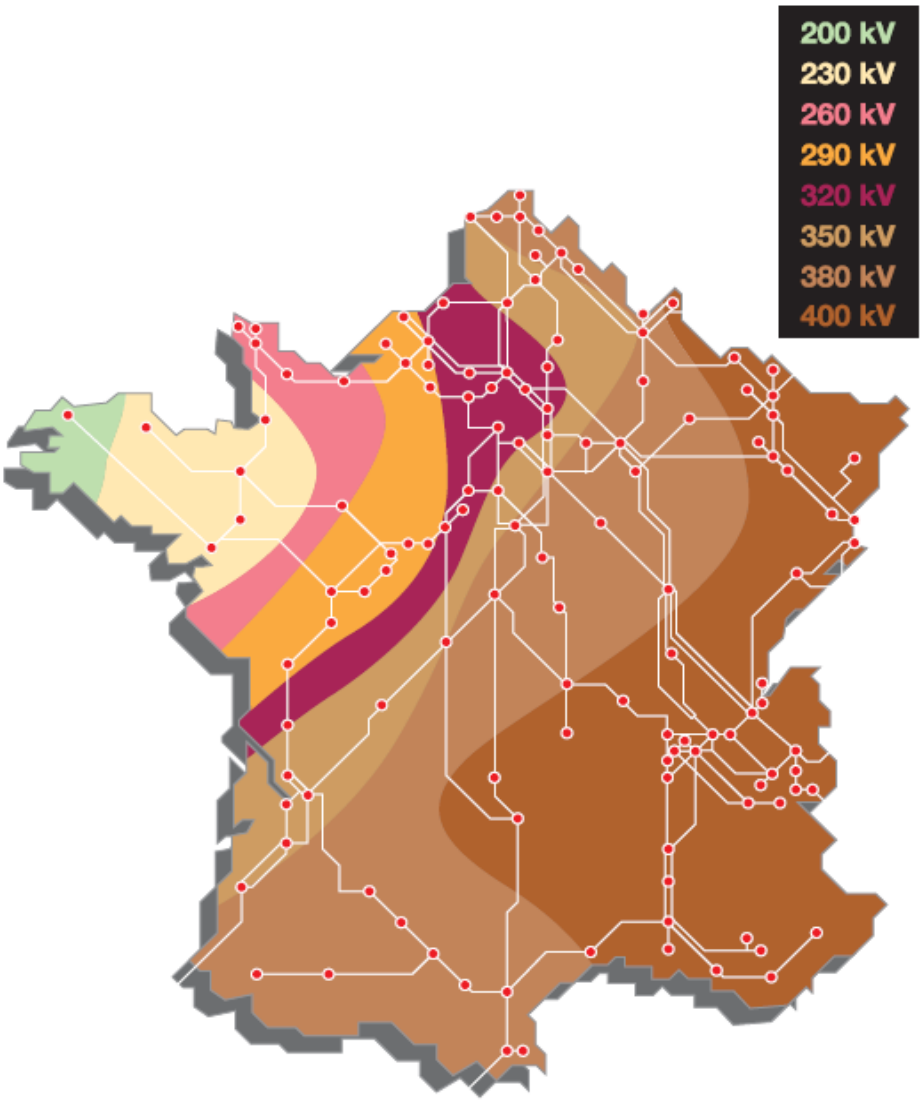


Figure 1.8 *Voltages on the French network after the 1987 incident* ***[13]***

Regarding the 2003 Switzerland-Italy problem, the initial situation was the following: night, important power flows between France and Italy as well as Switzerland and Italy and 225 kV and 400 kV transmission lines highly loaded in the North of Italy. The first incident was the line tripping of the Lavorgo-Mettlen line caused by tree flashover. It wasn't possible to reconnect this line either automatically or manually. A second line was tripped twenty-four minutes later due to overloading (Sils-Soazza) and then a third one (Airolo-Mettlen). After these three line tripping, the Italian network was losing the synchronism with the European network and so all remaining connecting lines on the cut-set between Italy and UCTE were disconnected by regular function of protection devices. After that disconnection, the Italian system was not able to avoid system collapse even with the actions of automatic and defense systems [14].

Figure 1.9 depicts the lines disconnections and Figure 1.10 shows the frequency evolution in Italy during the incident and are taken from [14].

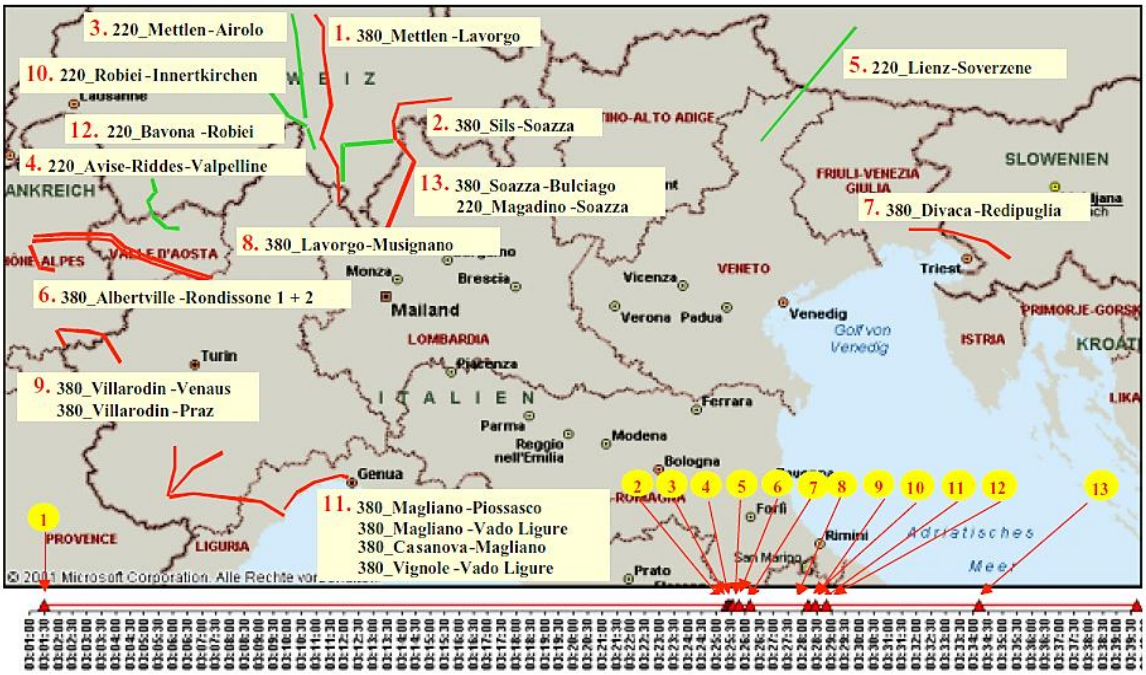


Figure 1.9 *Line tripping during the 2003 Switzerland-Italy incident* ***[14]***

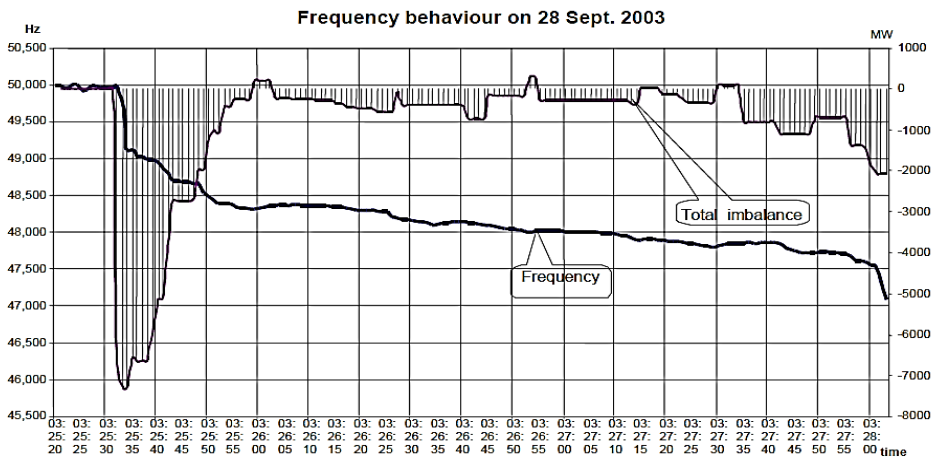


Figure 1.10 *Frequency evolution in Italy during the incident* ***[14]***

1.4 AIM OF THE MASTER'S THESIS AND OVERVIEW OF THE REPORT

We have seen that RTE and all the TSOs have the mission to guarantee high reliability of supply and high quality of electricity whatever the conditions in a context which is changing. In order to achieve this goal, they must ensure power system security and respect the (N-1) criterion.

The aim of this Master's thesis has been to ensure the voltage stability in some parts of the French network. More practically this project has been initiated by RTE R&D in order to update the static criteria which were used on the North-East and the East areas, the consumption level at which an automatic load-shedding device should be activated and to make different tests on the network such as changes in the time constants for the load-tap changers and measure their impacts. These updates are necessary due to the changes that have been presented before (evolutions of the grid, increase of the consumption). However, the goals of the Master's thesis have evolved during the work and with the results obtained. Finally, the static criteria on the North-East and the East areas have been suppressed and on-line dynamic studies will now be done instead for these areas. In order to get better results, the characteristics of some power plants of the neighboring countries have been added and tests have been done to validate these evolutions which are now used in operational context (from week-ahead to quasi real-time simulations).

In this report, we start by introducing the topic with the presentation of RTE, the company in which the Master's thesis work has been done. We then present the context of power system, the importance of power system stability and the different kind of power system stabilities in a first chapter. Theoretical background about voltage stability is provided into the second chapter. Voltage stability has been at the heart of the work done during this Master's thesis. Basic notions are presented in a first section on a simple example in order to have a first view of voltage stability. The importance of load modeling for these problems is then presented. The second chapter ends with a presentation of French voltage control mechanisms and some methods used in France to limit the consequences of voltage problems. Chapter 3 is devoted to the description of the software and methodologies used during the Master's thesis. The report then focuses on the simulations led, the conclusions that have been drawn from these simulations and their results and the global evolution of the work as explained in Chapter 4. Finally the report ends with a closure which, after giving a summary of the work done and its consequences, presents general conclusions and recommendations and opens new perspectives for future studies.

2 THEORETICAL BACKGROUND

2.1 INTRODUCTION TO VOLTAGE STABILITY

2.1.1 BASIC EQUATIONS AND NOTIONS

In order to understand the issue of long-term voltage stability, we will begin with a simple example. Indeed, with complex networks, it is difficult to highlight the phenomena at work in voltage decrease and system collapse.
We will consider a perfect generator (a generator that is a constant voltage source), a purely resistive load and a line between them. The line is represented as purely inductive (the more important the power flow will be, the more accurate this model will be). The system is shown in Figure 2.1.

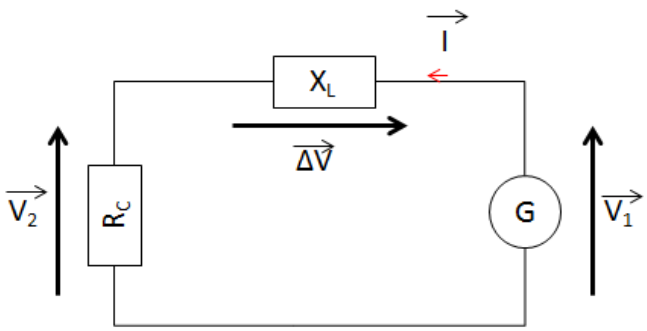


Figure 2.1 *Simple system for voltage stability analysis*

Let P_2 be the active power consumed in the load.
Let φ be the phase difference between V_2 and I
We have:

$$P_2 = V_2 I cos(\varphi) \tag{2.1}$$

Here $\varphi = 0$ because the load is purely resistive. So:

$$P_2 = V_2 \frac{\Delta V}{X_L} \tag{2.2}$$

If we represent the system on a phase diagram (see Figure 2.2), we have:

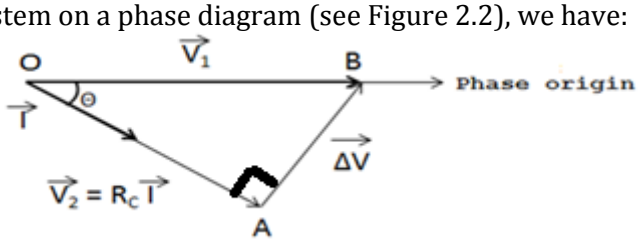


Figure 2.2 *System phase diagram*

From Figure 2.2, we have:

$$AB^2 = OB^2 - OA^2 \ \ that\ is\ \ \Delta V^2 = V_1^2 - V_2^2 \qquad \textbf{(2.3)}\ and\ \textbf{(2.4)}$$

Thus:

$$P_2 = \frac{V_2}{X_L}\sqrt{{V_1}^2 - {V_2}^2} \qquad \textbf{(2.5)}$$

Based on equation (2.5), it is possible to represent the voltage value V_2 as a function of the active power P_2 (Figure 2.3).

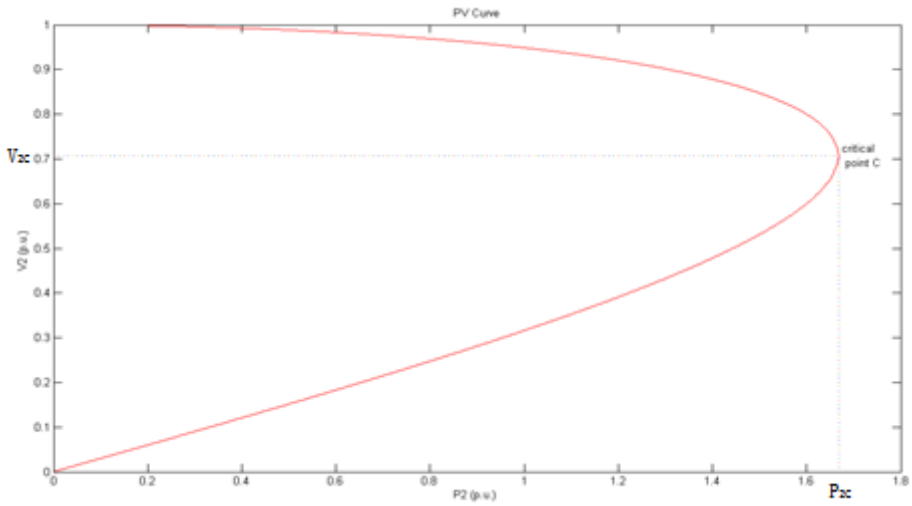


Figure 2.3 *Transmissible power for a simple system*

As seen in Figure 2.3, the active power consumed in the load is equal to the maximum transmissible power through the line at point C. The values of the critical point C (V_{2C}, P_{2C}) can be easily determined in this simple example.

We have found in (2.1) that:

$$P_2 = V_2 I$$

But we also have from the phase diagram (Figure 2.2) and equation (2.3):

$$OB = \sqrt{OA^2 + AB^2}\ that\ is\ V_1 = \sqrt{R_c I^2 + X_L I^2} \qquad \textbf{(2.6) and (2.7)}$$

and so :

$$I = \frac{V_1}{X_L\sqrt{1+(\frac{R_C}{X_L})^2}} \qquad \textbf{(2.8)}$$

$$V_2 = R_C I = \frac{R_C V_1}{X_L\sqrt{1+(\frac{R_C}{X_L})^2}} \qquad \textbf{(2.9)}$$

By defining $Y_C = \frac{1}{R_C}$, we get:

$$I = \frac{V_1}{X_L\sqrt{1+(\frac{1}{Y_C X_L})^2}} \; and \; V_2 = \frac{V_1}{\sqrt{(Y_C X_L)^2+1}} \qquad \textbf{(2.10) and (2.11)}$$

From these two equations, another expression of the active power consumed by the load is derived:

$$P_2 = \frac{{V_1}^2}{Y_C X_L(1+\left(\frac{1}{Y_C X_L}\right)^2)} = \frac{\frac{{V_1}^2}{X_L}}{(x+\frac{1}{x})} \; by\ setting\ x = Y_C X_L \qquad \textbf{(2.12)}$$

By differentiating this equation (X_L and Y_C are the only parameters that can vary because we consider that V_1 is constant) and setting the derivative equal to zero, the maximum active power transmissible by the line can be obtained:

$$\frac{dP_2}{dx} = 0 => 1 - \frac{1}{x^2} = 0 => x = Y_C X_L = 1$$

and so :

$$R_C = X_{L,} \; V_{2C} = \frac{V_1}{\sqrt{2}} \; and \; P_{2C} = \frac{{V_1}^2}{2X_L} \qquad \textbf{(2.13) and (2.14)}$$

Here we find a well-known result which is that the maximum power transmissible is obtained when the load impedance is equal to the line impedance. It is impedance matching.

We also have a second equation for the active power consumed in the load:

$$P_2 = \frac{{V_2}^2}{R_C} \; and\ so\ V_2 = \sqrt{P_2 R_C} \qquad \textbf{(2.15)and (2.16)}$$

For R_C, X_L and V_1 given, the equilibrium point of the system must satisfy the equation (2.5) and the equations (2.15)and (2.16) and so it is the intersection of the two curves (see Figure 2.4).

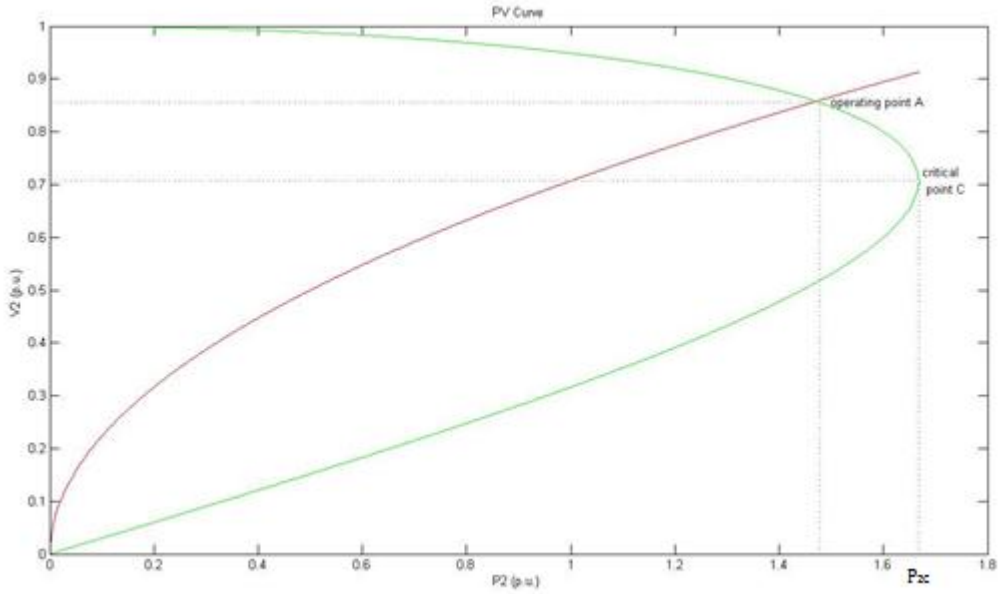


Figure 2.4 *PV Curve for the simple system with R_C = 0.5 p.u., X_l = 0.3 p.u. and V_1 = 1 p.u.*

If now we consider that it is the active power consumed that is set, we can have three possible situations:

- $P_{2set} > P_{2C}$: there is no equilibrium point
- $P_{2set} = P_{2C}$: there is only one equilibrium point, the critical point
- $P_{2set} < P_{2C}$: there are two equilibrium points

We will focus on the situation with two possible equilibrium points: one on the top part of the curve, the other one on the bottom part of the curve. These two points correspond to two different resistance values and to two different states in the system. However, these two points are not equivalent. Indeed, for the lower equilibrium point, in order to transfer the same amount of power, the current through the line will be larger than the current needed with the upper point and so the reactive losses ($Q_l = X_l * I^2$) will be significantly higher [10]. Moreover, the voltage value is lower with the lower equilibrium point. For these reasons, the upper point is considered as the normal operating condition and the stable solution.

2.1.2 INFLUENCES OF THE DIFFERENT PARAMETERS

We will see now the influences of the different parameters on the coordinates of the critical point.

2.1.2.1 INFLUENCE OF THE CONSTANT VOLTAGE VALUE V_1

In this part, we consider that the line impedance X_L is set. We will study the impact of a change of V_1, the value of the constant voltage source. In the previous section, we have established the following equations (2.13) and (2.14):

$$P_{2C} = \frac{{V_1}^2}{2X_L} \; and \; V_{2C} = \frac{V_1}{\sqrt{2}}$$

We can notice from these two equations that the voltage value V_1 has an effect on both the critical voltage and the maximum transmissible power (maximum transmissible power varies with the square of V_1 when critical voltage varies with V_1 only).

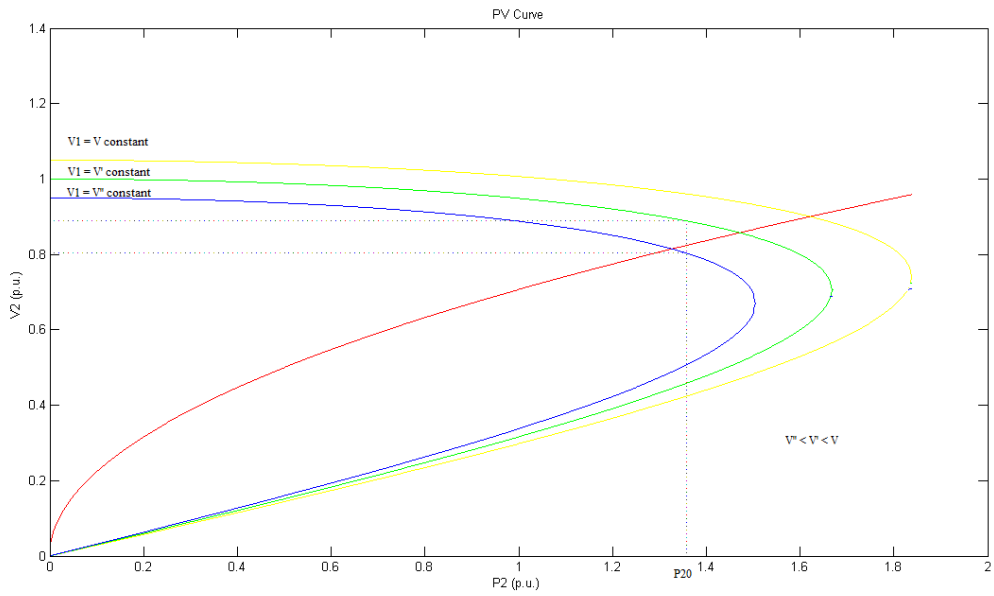


Figure 2.5 *Influence of V1 on the PV curves (V1 = 0.95 p.u., 1 p.u. and 1.05 p.u.)*

For a predetermined value of P_2 (P_{20}), we observe that the operating point voltage is higher when the constant source voltage V_1 is higher. Figure 2.5 highlights the importance to maintain a high voltage setting point for the generators in order to have higher voltage at the load centers and to have a larger distance between the current transmissible power and the maximum transmissible power for a predetermined value of the current transmissible power.

2.1.2.2 INFLUENCE OF THE LINE IMPEDANCE X_L

The influence of the line impedance will be spotlighted in this section. By way of consequence, the voltage source is set and only X_L will change. We know from the equations (2.13) and (2.14) that the critical voltage V_{2C} remains the same regardless the value of X_L. However, the critical active power consumed by the load decreases when X_L increases (Figure 2.6).

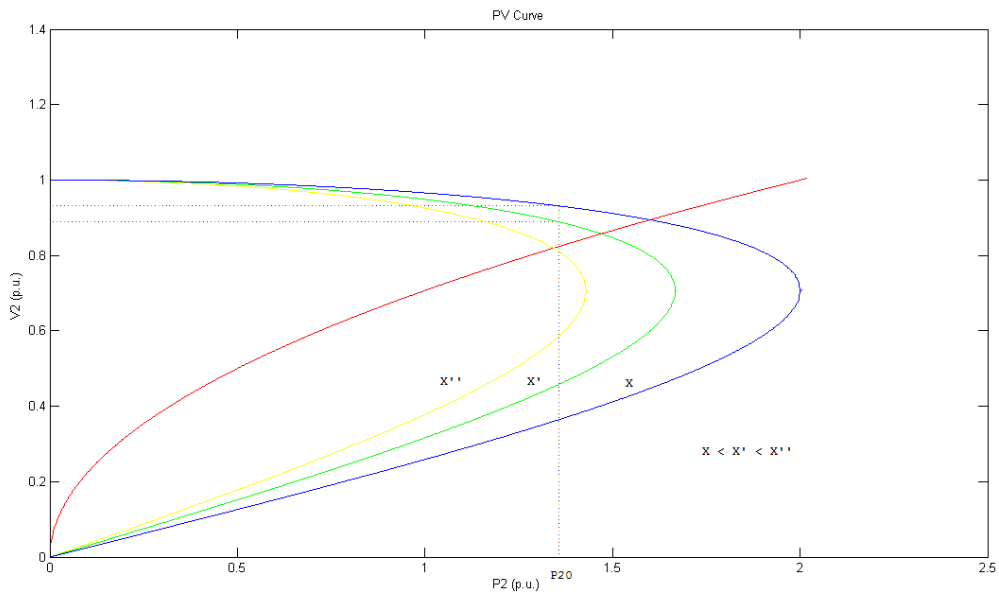


Figure 2.6 *Influence of Xl on the PV curves (Xl = 0.25 p.u., 0.3 p.u and 0.35 p.u.)*

For a predetermined value of P_2, the operating point is higher with a lower value of X_L and the distance between P_{20} and the critical active power is also larger with a lower value of X_L. It is thus important to keep a low value of line impedance in order to have acceptable voltages on the network.

We can take from [10] another simple example to illustrate this notion: the Single-Load Infinite Bus system shown in Figure 2.7. This simple system may represent a generation area from which power is delivered to a load area via a transmission system with long lines. We consider that we have η parallel lines and each parallel line is represented by a series reactance x so $X_{eq} = \frac{x}{\eta}$. When the number of lines decreases, the operating point has a lower voltage value and the critical active power also decreases (Figure 2.7)

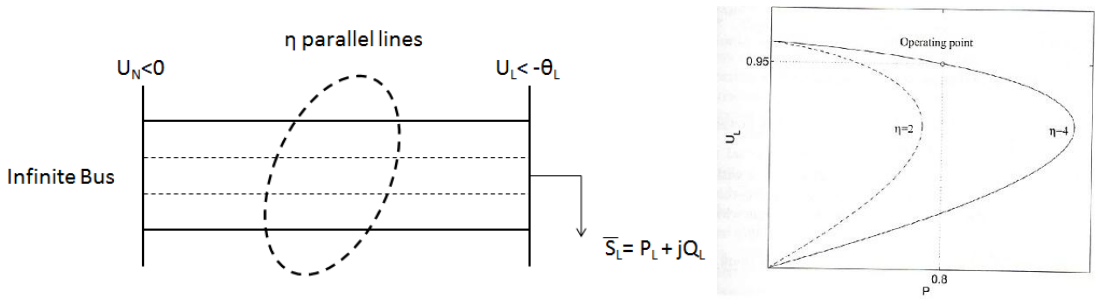


Figure 2.7 *Influence of the transmission lines number for the SLIB system* ***[10]***

2.1.2.3 INFLUENCE OF THE LOAD IMPEDANCE Z_C

In this part, we will consider a load impedance that is no longer a simple purely resistive load. So we have:

$$Z_C = R_C + jX_C \; and \; \tan\varphi = \frac{Q_2}{P_2} \qquad \textbf{(2.17) and (2.18)}$$

We can derive the formula linking the active power consumed P_2 and the voltage value V_2:

$$P_2 = \frac{{V_2}^2 \cos(\varphi)}{Z_c} \qquad \textbf{(2.19)}$$

It is then possible to plot the curves for different values of *tan φ*. Figure 2.8 has been taken from [12] and is equivalent to the simple example with the purely resistive load replaced by a load impedance.

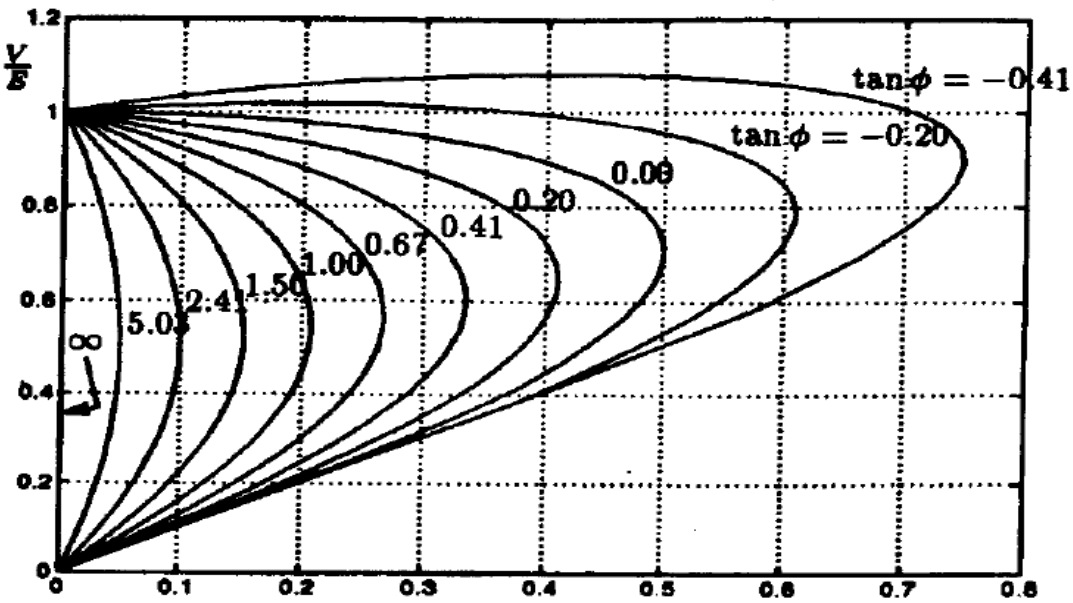


Figure 2.8 *Nose curves* ***[12]***

What we can notice from these curves is that a decrease of the *tan φ* algebraic value leads to an increase of the operating voltage value and an increase of the critical active power consumed by the load. Adding capacitors in parallel at the load bus will decrease the *tan φ* algebraic value so is benefic for the voltage stability of the system. It will also allow for more important power flows through the lines. Nevertheless, there is a drawback: the addition of capacitors will also increase the critical voltage value and so the normal operating point will have a voltage value closer to the critical voltage value. It is also possible to use inductors in order to decrease the voltage value when TSOs have to face issues linked to too high voltage values (for example during the summer when the load is low). Some controllable capacitors are installed in the French network and can be switched on during voltage crisis in order to keep acceptable voltage levels.

2.1.2.4 INFLUENCE OF THE GENERATOR LIMITATIONS

In this section we will consider the limitations of the generator. It will no longer be considered as a perfect generator which can be represented as a constant voltage source. A real generator doesn't have unlimited reactive reserves as can be seen on Figure 2.9.

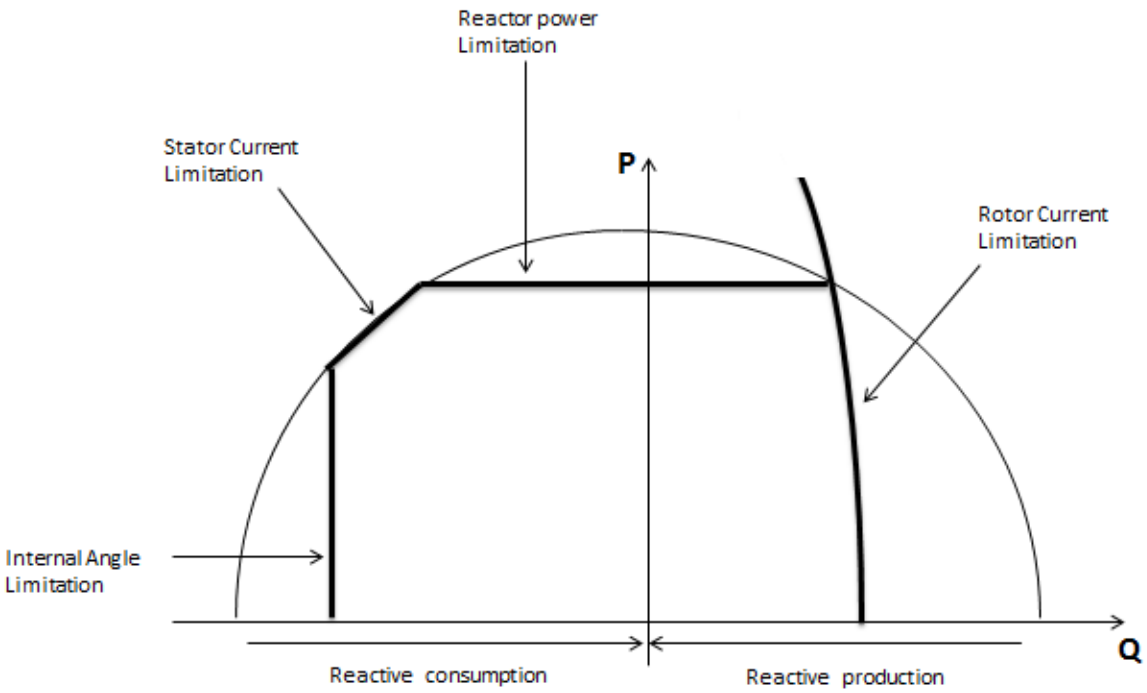


Figure 2.9 *Usual operation limitations for a generator*

As we are interested in voltage crisis with risk of system collapse, the generators are providing reactive power to the system and the only limitation that is important for us is the rotor current limitation. In order to respect the rotor current limitation, a rotor current control loop is installed on the voltage controller of many units in the French grid. If the rotor current exceeds the maximum possible value, the loop is solicited and the voltage value set point is decreased in order to reduce the rotor current to its maximal possible value. Once the unit has hit the rotor current limitation, it is no longer a constant source voltage but a generator with a quasi-constant reactive power production.

In order to see the impact of this limitation, we will still use the simple example presented in 2.1.1 and derive a formula linking the reactive power production Q_1, the active power consumed P_2 and the voltage V_2 for this example. We have:

$$Q_1 = V_1 I \sin(\theta) \; and \; V_1 \sin(\theta) = \Delta V \; (phase\ diagram, \text{Figure 2.2 }) \qquad \textbf{(2.20) and (2.21)}$$

$$so\ Q_1 = I\,\Delta V = \frac{\Delta V^2}{X_L} = \frac{{V_1}^2 - {V_2}^2}{X_L} \qquad \textbf{(2.22)}$$

And (2.5):

$$P_2 = \frac{V_2}{X_L}\sqrt{{V_1}^2 - {V_2}^2}$$

By taking the square of these two equations (2.5) and (2.22), we get:

$$V_1{}^2 - V_2{}^2 = X_L{}^2 \frac{P_2{}^2}{V_2{}^2} = Q_1 X_L \qquad \textbf{(2.23)}$$

And finally a relation between Q_1, P_2 and V_2:

$$V_2 = P_2 \sqrt{\frac{X_L}{Q_1}} \qquad \textbf{(2.24)}$$

As a consequence, for a production-transport system, the evolution of V_2 taking into account the rotor current limitation is completely described (Figure 2.10) by:

- the parabola on Figure 2.10 corresponding to (2.5) when $Q_1 < Q_{limit} \Leftrightarrow I_{rotor} < I_{max}$
- the straight line on Figure 2.10 corresponding to (2.24) when the rotor current hits the rotor current limitation

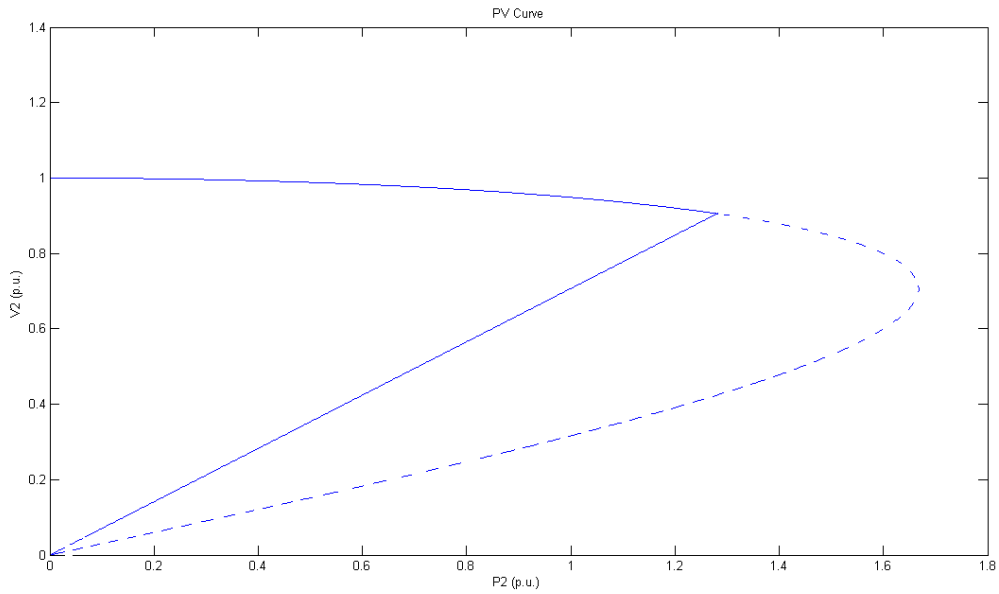


Figure 2.10 *Influence of the rotor current limitation on PV curve*

It is noticeable from the Figure 2.10 that the rotor current limitation decreases the maximum transmissible active power. In operating conditions, it is good to try to take a reactive margin in order not to hit the rotor current limitation. However, during voltage crisis and peak consumptions, it is sometimes impossible and the power plants sometimes hit their rotor current limitation.

We have presented in this part the basis of voltage stability and tried to highlight the influence of different parameters. After this introduction to voltage stability, the next part is devoted to the presentation of load-tap changers (LTCs) and load models.

2.2 CONSUMPTION REPRESENTATION AND ITS IMPACT

In this part, we will focus on the behavior of LTCs and the load modeling. These aspects are crucial in long-term voltage stability issues.

2.2.1 LOAD MODELING

Load modeling is essential in voltage stability analysis. The loads voltage dependence requires consideration. It is generally represented with an exponent or a polynomial model ([10], [11] and [12]).

The exponent load model is:

$$P = P_0(\frac{V}{V_0})^{\alpha} \; and \; Q = Q_0(\frac{V}{V_0})^{\beta} \qquad \textbf{(2.25)and (2.26)}$$

The value of the exponent describes the load voltage dependence. Integer values of exponents zero, one and two correspond to constant power, current and impedance loads respectively. Typical values of the exponents for different load components are presented below [11]:

Load Type	α	β
Electrical Heating	2.0	- (Q = 0)
Television	2.0	5.2
Refrigerator/freezer	0.8 – 2.11	1.89 – 2.5
Fluorescent lighting	0.95 – 2.07	0.31 – 3.21
Frequency drives	1.47 – 2.12	1.34 – 1.98
Small industrial motors	0.1	0.6
Large industrial motors	0.05	0.5

Table 2.1 *Typical values for load model exponents* ***[11]***

The polynomial load model is:

$$P = P_0\left[Z_P\left(\frac{V}{V_0}\right)^2 + I_P\left(\frac{V}{V_0}\right) + P_P\right] \; and \; Q = Q_0\left[Z_Q\left(\frac{V}{V_0}\right)^2 + I_Q\left(\frac{V}{V_0}\right) + P_Q\right] \qquad \textbf{(2.27) and (2.28)}$$

Some measured values for the parameters of the polynomial load are given in the next table from [11]:

Parameter	Refrigerator/ Freezer	Fluorescent lighting	Frequency drives
Z_p	1.19	0.16	3.19
I_p	- 0.26	0.79	- 3.84
P_p	0.07	0.05	1.65
Z_q	0.59	0.18	1.09
I_q	0.65	- 0.83	- 0.18
Q_q	- 0.24	- 0.35	0.09

Table 2.2 *Measured values of polynomial load model parameters* ***[11]***

The organization of comprehensive measurements for the determination of load parameters in the whole power system is a time-consuming task. It requires measuring of load and voltage at each substation separately and during long and various periods. The measurement should take into account various aspects such as the days of the week or the weather conditions.

The properties of the exponent load model are presented in Figure 2.11 from [11] for a two bus system with a perfect generator bus, a line and a load bus for two values of α (α = 0.7 in the first one and α = 1.3 in the second one).

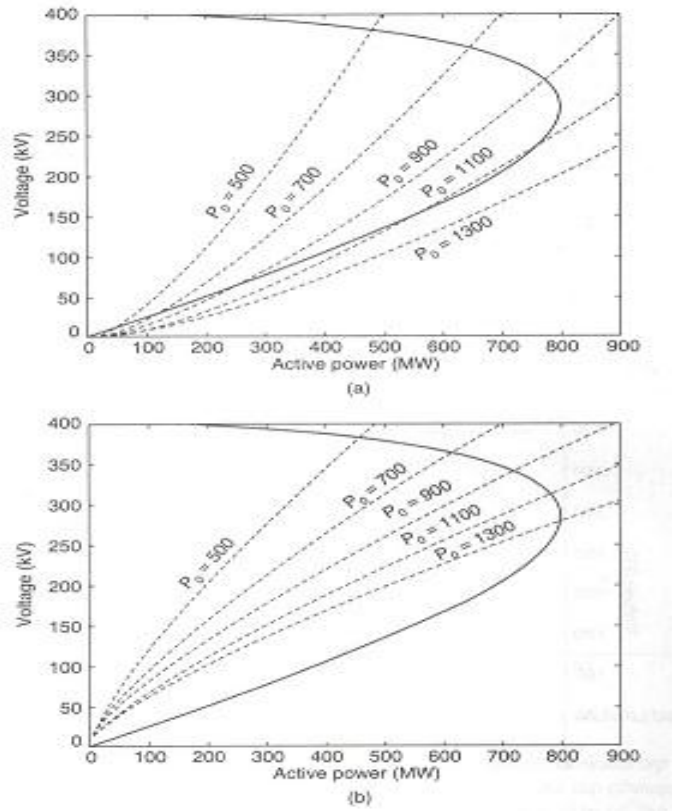


Figure 2.11 *Exponent load model with α = 0.7 (a) and α =1.3 (b)*

When α is equal to 0.7, the maximum loading point occurs when the nominal load is around 1 000 MW whereas when α is equal to 1.3, the maximum loading point is reached with a nominal load equal to 1 300 MW.

The model chosen for the load voltage dependence plays an important role in voltage studies. The general model adopted by RTE for its studies is an exponent model with α = 1 and β = 2. However, measures are currently being done in order to improve this model.

2.2.2 LOAD-TAP CHANGERS

A load-tap changer is a transformer with variable turns-ratio (or tap-changer n). Its function is to automatically control the voltage at the load node by changing the tap. Generally speaking, the tap is situated on the high voltage side where it is easier to change it since the current on this side is lower. A LTC also has a minimum and a maximum tap position which are the limits of the tap-changer. The voltage value on the low voltage side is:

- $V_{low} = V_C$ if the LTC doesn't hit its limits
- $V_{low} = V_{high} / n_{MIN}$ if the tap is at its minimal value
- $V_{low} = V_{high} / n_{MAX}$ if the tap is at its maximal value

In order to study the LTCs impact on the voltage in more details, we will use the SLIB system. Two assumptions are also made: the load is purely resistive and the dynamic of the load-tap changer is considered continuous. This example has been developed in [10] and the Figure 2.12 demonstrates the system used.

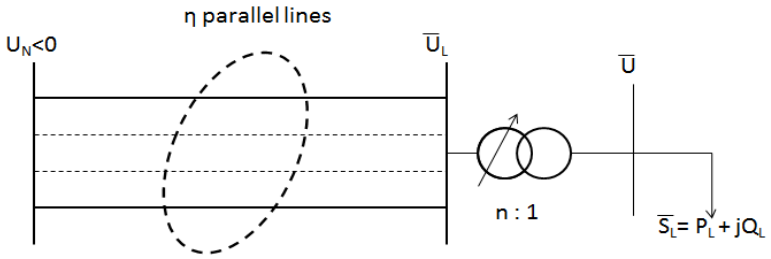


Figure 2.12 *SLIB system modified by the LTC addition* ***[10]***

The equations describing the behavior of the system are:

$$U = \frac{U_L}{n}, \dot{n} = \frac{1}{T}(U - U_0) = \frac{1}{T}\left(\frac{U_L}{n} - U_0\right) \text{ and } \overline{S_L} = P_L = \frac{U^2}{R_L}$$ ***(2.29), (2.30) and (2.31)***

where T is a time constant representing the time interval between two tap positions.

The time constants used for LTCs simulation in RTE are 30 s for the first tap change and 10 s between each tap change for transport LTCs and 60 s for the first tap change and 10 s between each tap change for distribution LTCs.

The following figure displays the system response after disconnection of a line in the transmission system:

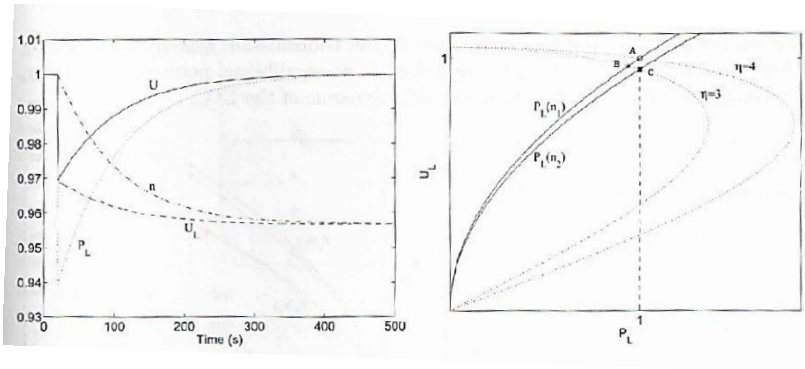


Figure 2.13 *Dynamic response of the system with η=3* ***[10]***

After the disconnection of the line, P_L, U_L and U decrease. The operating point moves from the intersection between the system characteristic with η=4 and the load-curve with $n=n_1$ (point A) to the intersection between the system characteristic with η=3 and the load curve with $n=n_1$ (point B). Then the LTC acts in order to restore the load voltage to its set point. The tap position moves, n decreases and the load voltage increases and so does P_L. An increase of P_L induces higher current through the remaining lines and higher reactive losses which causes further voltage reduction. This situation continues until the load is restored to its original value ($P_L = P_{L0}$ and $U_L = U_{L0}$). It corresponds to a shifting of the operating point from B to C due to LTC action. As there is still an intersection between the system characteristic curve and the dynamic load characteristic curve, the system is stable and there is no collapse.
If another lien is disconnected, the mechanism is the same with a new system characteristic curve with η=2. Nevertheless, this time, there is no intersection between the system characteristic curve and the dynamic load characteristic curve. So the LTC will first try to restore the load by decreasing n and increasing U_L and P_L and so the current through the remaining lines and the reactive losses. But the LTC can't restore the load (because there is no intersection between the two characteristic curves) and when P_L (n) crosses the critical voltage (point D) and enters into the lower side of the PV curve the load restoration has failed and U and P_L decrease leading to system collapse (Figure 2.14).

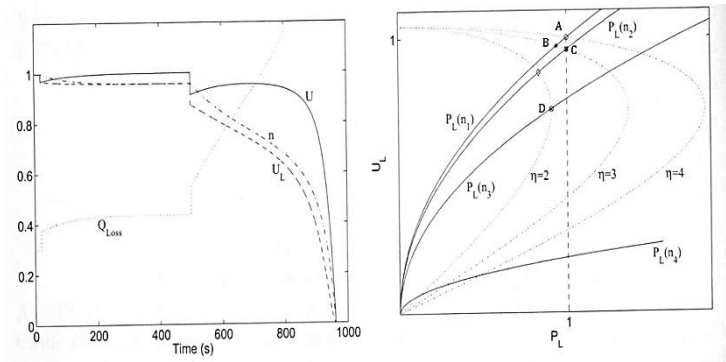


Figure 2.14 *Dynamic response of the system with η = 2* ***[10]***

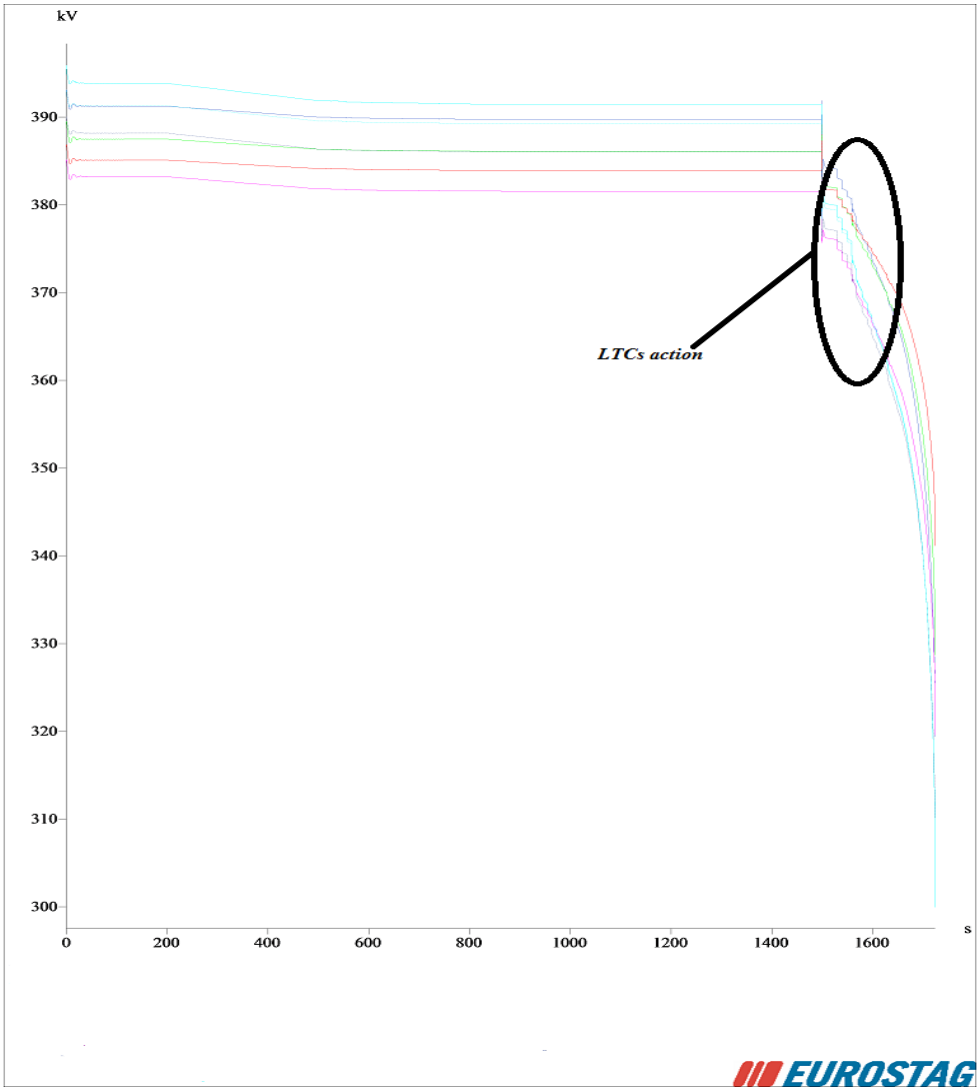


Figure 2.15 *Illustration of LTCs effect*

Figure 2.15 is another example taken from a Eurostag software simulation that shows the LTCs importance in system collapse. LTCs are very important components of the system regarding voltage stability and can accelerate a voltage decrease by their actions thus leading the system to collapse.

In this part, the impact of the load model and the behavior of LTCs have been presented. Their role in the voltage stability studies is essential. The next step will be the description of some voltage control mechanisms and some devices and methods used to face voltage issues in France.

2.3 VOLTAGE CONTROL MECHANISMS AND PREVENTION OF VOLTAGE INSTABILITY AND COLLAPSE IN THE FRENCH SYSTEM

In this section, voltage control mechanisms on the transmission system and particularly secondary voltage control system (SVC) and secondary coordinated voltage control system (CSVC) used in France are presented. In a second time, a device and some methods used to avoid voltage instability or at least to limit the voltage instability probability are introduced.

2.3.1 VOLTAGE CONTROL MECHANISMS

2.3.1.1 GENERAL INTRODUCTION

There are three different levels for voltage control on the French EHV network [15]. These three mechanisms are temporally and spatially independent:

- the primary voltage control that is used to compensate rapid random and local variations of the load or small incidents. It keeps generator stator voltages at their set-point values by means of controls fitted to all the generating units. Its time-scale is around ten seconds.
- the SVC or the CSVS are used to compensate for slower voltage variations. It uses the reactive reserves of the power plants to adjust the voltage at a specific point. Their time-scale is a few minutes.
- the tertiary voltage control. It is applied to optimize the nationwide voltage map. It involves determining voltage set-points for the pilot points in order to achieve safe and economic system operation. It is done manually but if an automatic process should be done, its time-scale will be around fifteen minutes.

We will now focus on SVC and CSVC.

2.3.1.2 SECONDARY VOLTAGE CONTROL AND COORDINATED SECONDARY VOLTAGE CONTROL

SVC and CSVC characteristics presented here are mainly taken from [15].

We will begin with SVC and then follow with CSVC, which is an improvement of the SVC installed on the Western part of France.

The SVC goal is to control the voltage value inside a geographical area by automatically acting on the reactive power production of the area units. This control should be done individually for each area and theoretically there should be no interactions between the different areas. In order to achieve this goal, SVC adjusts the reactive power productions of the units in order to control the voltage at a specific point (known as the pilot point) in the area. The voltage at the pilot point is considered representative of all area node voltages.

The SVC system inputs the instantaneous voltage measured at the area pilot point, compares it with the voltage set-point, and applies a proportional-integral law to determine a signal representing the reactive power level required for this zone. This signal is then used to determine a set-point for the reactive-power control loop of each generating unit. Steady-state

reactive power generation is therefore aligned, with each generating unit contributing to the total reactive power requirement proportionally to its capabilities.

The SVC system has advantages for the operation of the network (voltage maintained in each area around a determined value, quick compensation after the loss of an important unit, etc.) and also from an economical point of view (by maintaining the voltage level, the losses are reduced; postponing the investments in capacitive units by a better use of the existing units, etc.). However, it also has limitations. These limitations can be either structural or design-related ones. For example, SVC works individually for each area with the hypothesis that there are no interactions between the areas. However, coupling between the areas has increased with the grid development and therefore the areas should be adapted. This example is a structural limitation of SVC.

In order to improve this SVC, a new system was developed: CSVC. Whereas the SVC system controls the voltage locally at the single point pilot, the CSVC system adjusts the voltage map for a whole region by controlling the voltages at a set of pilot points, using a set of set-point values. In order to do that, it minimizes a multi-variable quadratic function and uses two sensitive matrices:

- sensitivity matrices relating variations in pilot point voltages to variations in stator voltages
- sensitivity matrices relating variations in reactive power productions to variations in stator voltages

There are three major benefits of CSVC compared to SVC:

- the voltage map is more stable and precise, with less reactive power demand on the generating units
- coordination improves the mobilization of reactive reserves available from generating units, by making higher demand on the units closest to the perturbation
- the CSVC system has a better dynamic response

CSVC is under operation on the Western area whereas SVC still operates on the other areas. Further information on these mechanisms can be found in [15], [16] and [17] in particular.

2.3.2 PREVENTION OF SYSTEM COLLAPSE

2.3.2.1 VOLTAGE SECURITY ASSESSMENT

Security assessment is a combination of system monitoring and contingency analysis. Security assessment is an analysis performed to determine whether, and to what extent, a power system is reasonably safe from serious interference to its operation. It involves the estimation of the relative robustness of the system in its present state or in the near future state [11].
This estimation is performed at different time-scales. From week-ahead studies to quasi real-time simulations, static criteria are used for three areas in France to assess the network security regarding voltage stability. Static criteria had been used on the entire French network during many years but were given up on four of the seven areas last year and replaced by on-line dynamic simulations. However, for three areas close to the borders, static criteria have been kept. These criteria should split the system states[2] between acceptable system states and undesirable system states. A system state is classified as acceptable when, for all the disturbances of a contingency list (generally all the busbar faults of the area), the criterion is still respected after the contingency. These criteria allow TSOs to verify that the system is respecting the (N-1) criterion. Otherwise, some measures will be applied in order to restore acceptable conditions for the network such as:

- disconnecting inductances
- connecting capacitors
- modifying the set point of the SVC 400 kV pilot points
- changing the network topology
- demanding the starting up of some generating units

After measures are applied, tests are simulated to check that measures were sufficient to restore acceptable conditions or not. Figure 2.16 shows the overall scheme representing the determination of security assessment by the static criteria use:

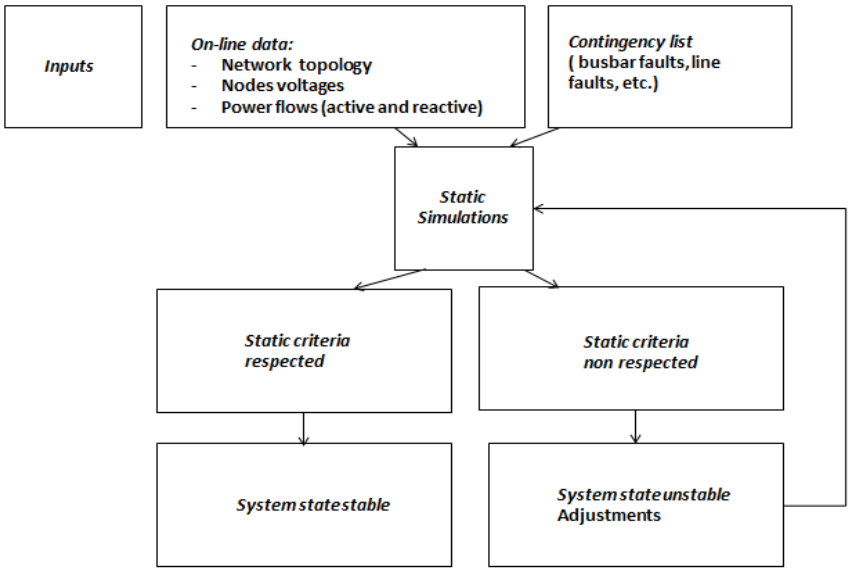


Figure 2.16 *Schematic diagram for voltage security assessment using static criteria*

[2] A system state is characterized at an instant by the consumption level, the generating units available and unavailable, the system topology, etc.

These criteria are very important because their use allow TSOs to verify that the system is in a state respecting the (N-1) criterion and otherwise, to take corrective measures to restore acceptable conditions.

2.3.2.2 AUTOMATIC LOAD-SHEDDING DEVICE (LSD)

An automatic load shedding device was installed on the French network three years ago. This automatic load shedding device is situated in a consumption area which supplied by a few production units – one coal power plant with four generators and three other generators –. This area is very weak regarding voltage stability. A disturbance in this area can lead to voltage decrease and system collapse.

This LSD, installed to avoid system collapses or at least too important voltage decreases, has two operating modes:

- A local or normal operating mode.
- A global operating mode.

In normal operating mode, the automaton controls the voltage value on seven reference nodes of the area. If the voltage becomes lower than the reference value on a reference node, then the device acts and sheds load on a list of nodes linked to the reference node. For each list of nodes, the device can reduce the load three times with a predefined value. There are temporizations associated to the device: it will shed load if and only if the voltage value becomes lower than the reference value during a certain time. With this mode, the LSD can shed maximum 4 500 MW of load in total. This normal mode is sufficient in many cases to restore a secure state after a disturbance.

The operation of the LSD normal mode is illustrated in the following example. After a consumption increase, the system is stabilized in an acceptable and steady state until a disturbance occurs, leading to a substantial voltage decrease. With the LSD normal mode activated, the system can overcome this disturbance and system collapse is avoided by three steps of load-shedding (10 s after the disturbance, 15 s after the disturbance and 16 s after the disturbance, see Figure 2.17). Without the LSD, the system is collapsing after the disconnection of other production units in addition to the disturbance (see Figure 2.18).

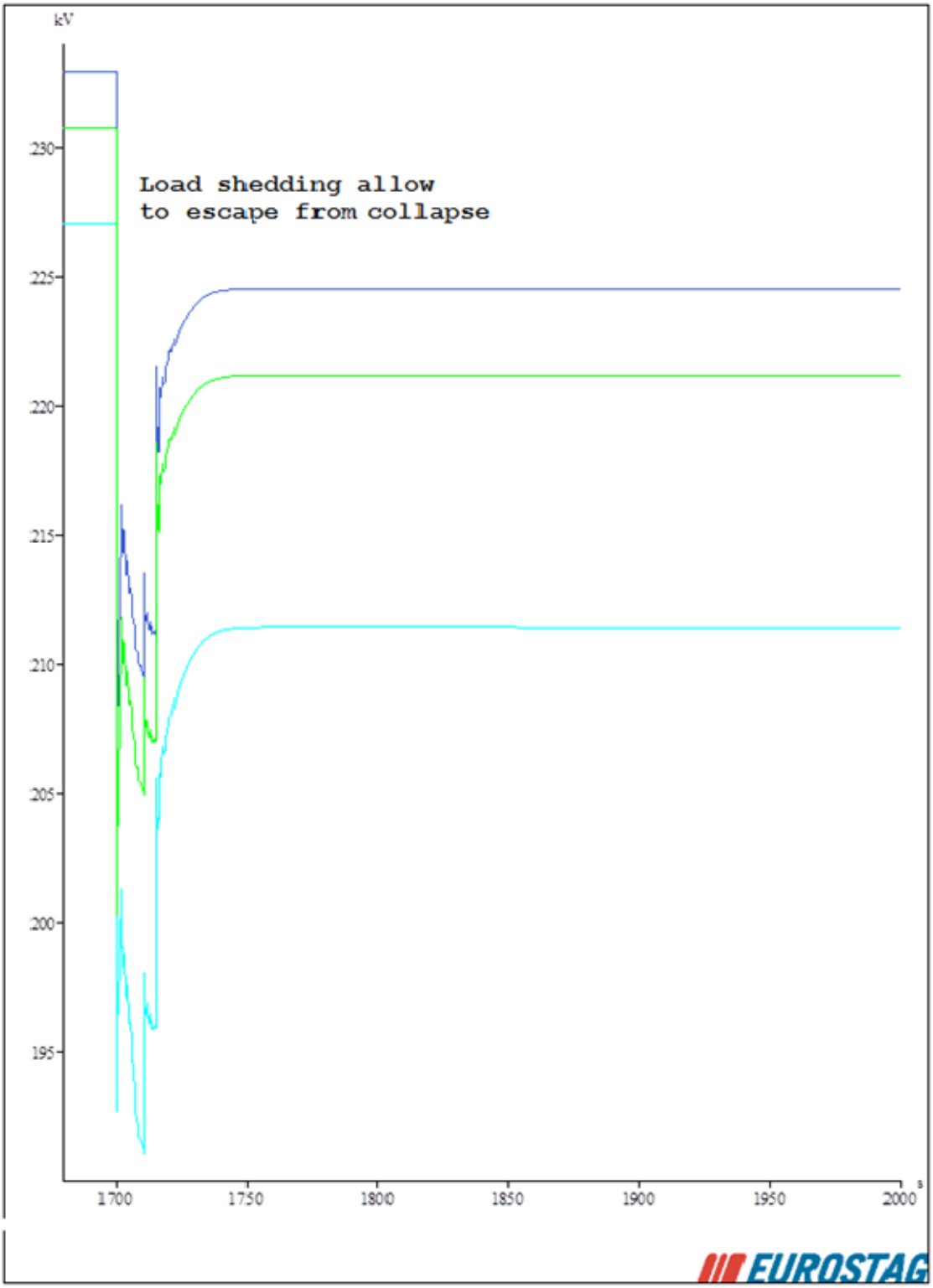


Figure 2.17 *Example of LSD action to escape system collapse*

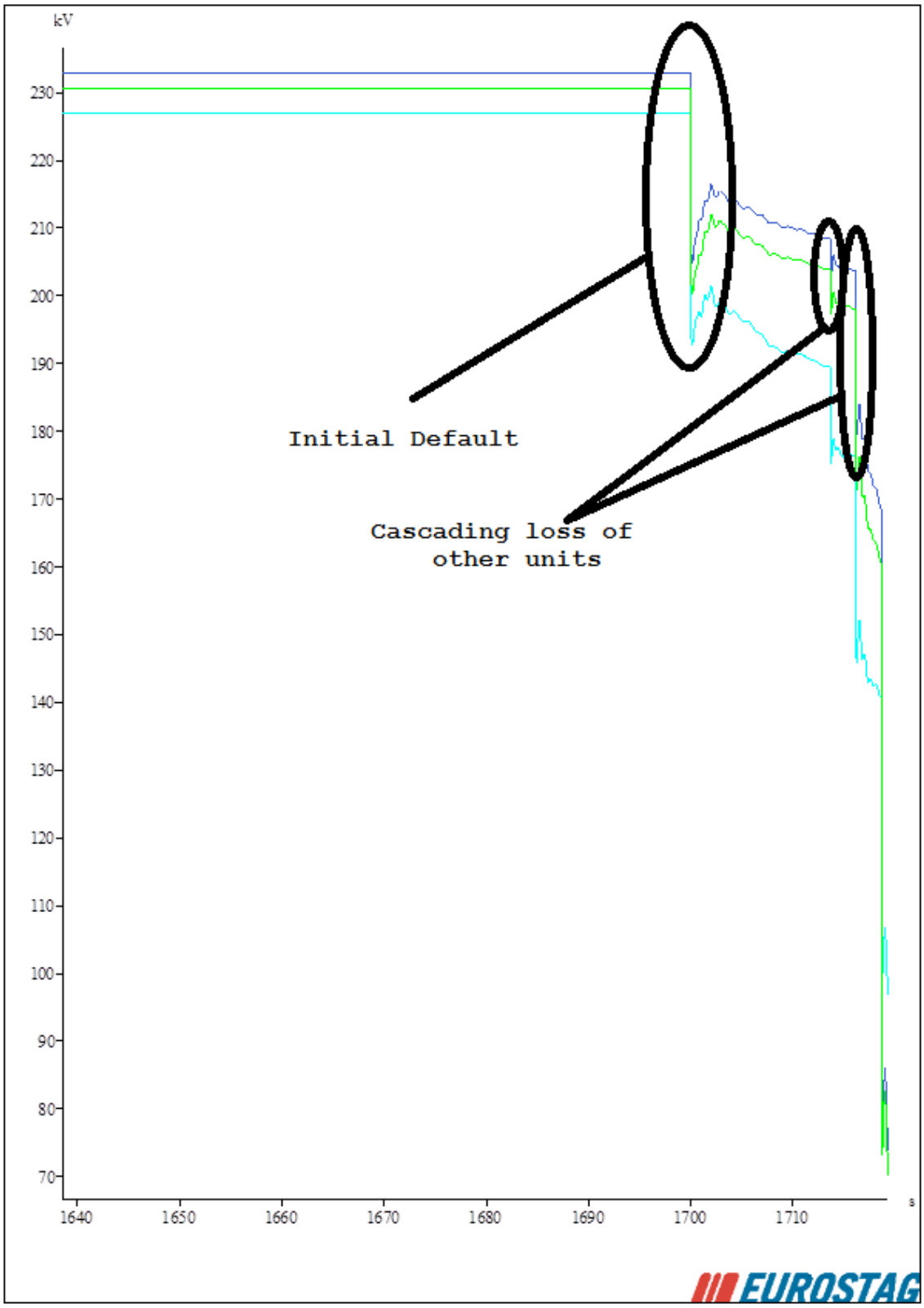


Figure 2.18 *System collapse without the LSD action*

However, for a particular kind of disturbance – the simultaneous loss of two generators from the coal power plant-, it was shown during the conception studies that a very quick collapse of the system was possible due to cascading losses of generating units. This disturbance can lead to the disconnections of the power plants close to this unit caused by undervoltage protection scheme. This undervoltage protection scheme is activated when the voltage at the connecting point of the power plant becomes lower than 0.8 U_n for 2.5 s. It can be concluded that the initial disturbance leads to cascading losses of close generating units and system collapse before the action of the LSD normal mode. In order to prevent this from happening, a second operating mode was created for the LSD. This mode, known as global mode, is activated only at very high consumption level. Indeed, this disturbance will lead to a fast system collapse if and only if the consumption is very high. If the LSD global mode is activated and detects this particular disturbance (there are sensors installed on the connections of the generators to the network), it will directly shed two steps for the seven zones, for a total amount of load equal to 3 000 MW.

Figure 2.19 shows the LSD operation modes.

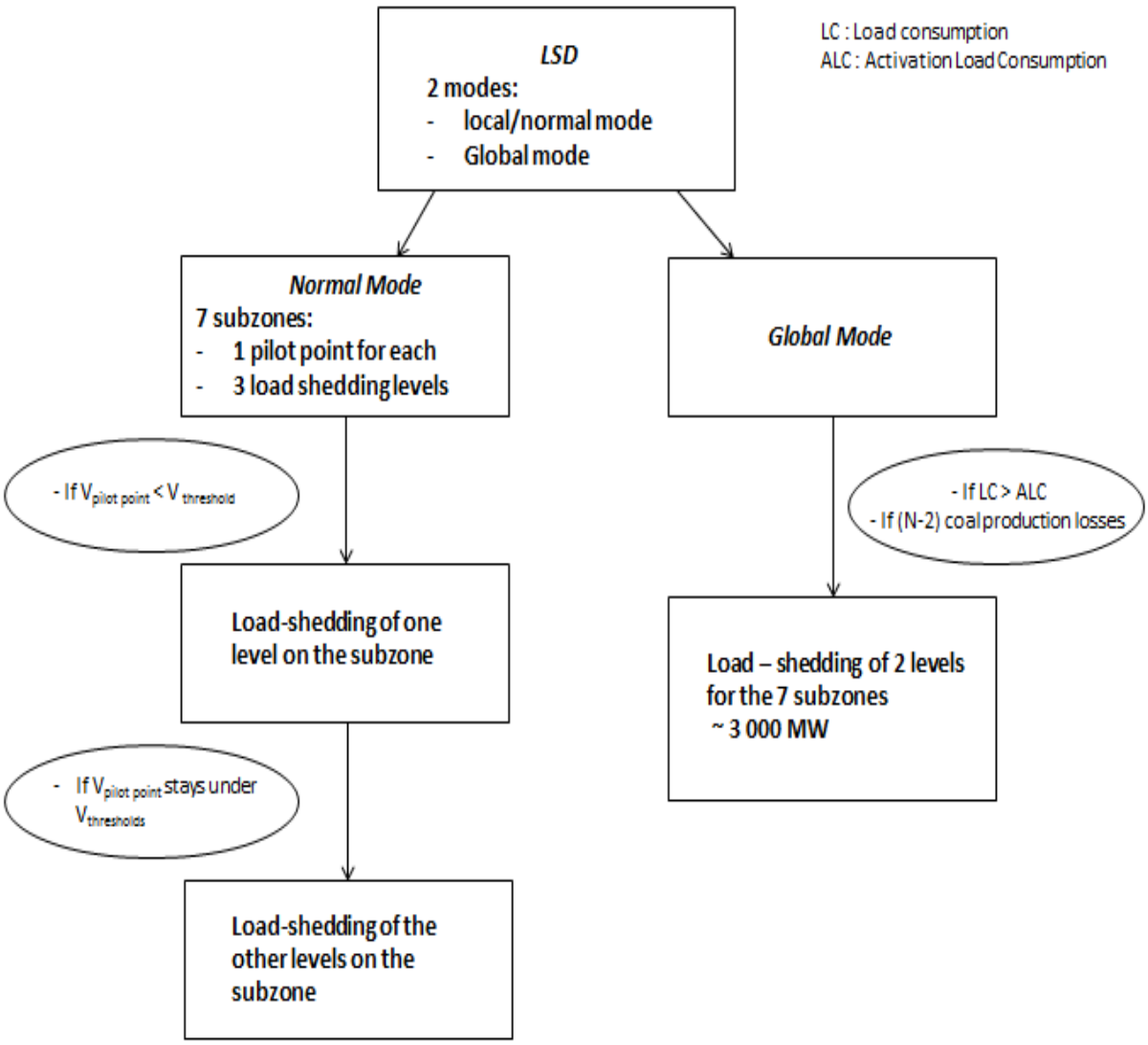


Figure 2.19 *Operating principle of the LSD*

2.3.2.3 BLOCKING OF LOAD-TAP CHANGERS

The operation of LTCs has been introduced previously and we have seen that their operation can accelerate voltage instability and system collapse by deteriorating even more a degraded situation in some cases. In order to avoid the negative impact introduced by LTCs, a tap position blocking scheme can be adopted.
The French network is divided in different areas and for each area, one or several pilot points are determined. For each of these pilot points, there is a minimum voltage value at this point and if the voltage becomes lower than the minimum voltage value, LTCs of the area are blocked after a constant time. The overall goal of this method is to avoid an amplification of the problem due to LTCs actions Indeed, when the voltage becomes lower than the minimum value at a pilot point, it means that there is a serious problem and a degraded situation and so LTCs action is negative. It is important to block the LTCs soon enough to avoid system collapse but it is also important to have minimal voltage values at the pilot points that are higher than the values observed during normal operation.

In this chapter, we have first introduced the major ideas linked with voltage stability by considering simple but representative examples. The influence of different elements of the model (generator, line, load, etc.) has been highlighted and then the model has been completed with load-tap changers, which play a crucial role in voltage stability dynamics. The different models of loads have also been presented. Finally, we focus more on the French network and present some of its particularities which are important for voltage stability and this Master's thesis: the load-shedding device, the static criteria and their role but also the secondary voltage control or the blocking principle of the load-tap changers. The software and some methodologies used during the work are explained in the next chapter.

3 SOFTWARE AND METHODOLOGIES USED

3.1 SOFTWARE USED DURING THE MASTER'S THESIS

For the different simulations and tasks that have been done during the Master's thesis, two tools have been used. Both of them are described in the following paragraphs: Convergence and Eurostag.

3.1.1 CONVERGENCE SOFTWARE

Convergence is software that consists of a static tool named Hades and a dynamic tool named Astre. It is a powerful software to run a great number of static simulations and dynamic simulations.

3.1.1.1 HADES SOFTWARE

Hades software is mostly used for load flow calculations. With this software it is possible to make load flow calculations for an initial state of the system N and for (N-1) system state after a disturbance is applied. The model inputs and outputs are demonstrated in Figure 3.1.

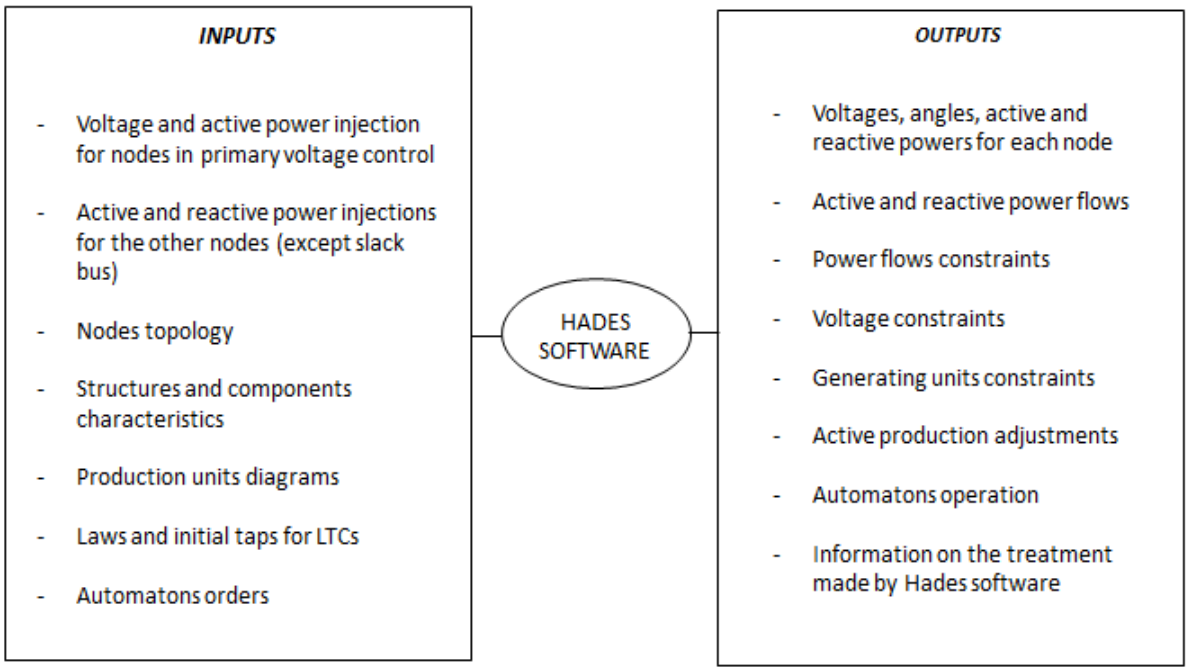


Figure 3.1 *Inputs and outputs from Hades software*

The user has a great number of available options. For example load flow calculations can be done with or without taking into account the actions of LTCs. When the LTCs action is considered, Hades software first calculates a solution without the LTCs action, then the connecting nodes of HV units are passed as (P,Q) nodes and the LTCs can change their taps (more equations are necessary to take into account the LTCs actions). Finally, a load flow is run with HV groups connecting nodes passed back as (P,V) nodes and a discretization of the load-tap position. The user also has the possibility for example to make topologies changes, to disconnect a power plant or to change the consumption in an area. Limitations such as maximum active and reactive power capabilities for the units are also taken into account in the model. After the calculation, the user can view the results and can for example see if there are lines that are overloaded. In conclusion, we can say that Hades software is a powerful load flow tool which is used in very different contexts: from quasi real-time simulations to prospective studies 20 years ahead.

3.1.1.2 ASTRE SOFTWARE

Astre is the dynamic tool included in Convergence software and is a voltage stability tool based on fast time-domain simulation engine. The core of Astre is a long-term dynamic security analysis software, which has been developed jointly by RTE and the University of Liège.
The major concept of Astre is to use quasi steady-state (QSS) approximation of long-term dynamics in order to speed up the calculations. It is done by neglecting the short-term dynamics of generators and their regulators, induction motors, Static VAR Compensators and HVDC components. In QSS simulations, these short-term dynamics are replaced by their equilibrium equations and the focus is on the long-term dynamics (LTCs dynamics, aggregate load recovery or secondary voltage and frequency control for example). The time step for the simulations chosen in RTE is ten seconds. The evolution of the system is then described by the four following equations:

$$0 = g(x, y, z_d, z_c) \quad \textbf{(3.1)}$$

$$\dot{x} = f(x, y, z_d, z_c) \Rightarrow 0 = f(x, y, z_d, z_c) \text{ with the QSS approximation} \quad \textbf{(3.2)}$$

$$z_d(k+1) = h_d(x, y, z_c, z_d(k)) \quad \textbf{(3.3)}$$

$$\dot{z_c} = h_c(x, y, z_c, z_d) \quad \textbf{(3.4)}$$

The first equation represents the algebraic equations derived from Kirchhoff's current law at each bus and involving the vector y of bus voltage magnitudes and phase angles. The second one is the short-term dynamics and is taken equal to zero with the QSS approximation. The two last equations are describing the long-term components behavior: the third one for discrete-type evolutions (typically LTCs operation or shunt compensation switching) and the fourth one for continuous-time evolutions (such as the aggregate load models).

This QSS method offers several significant advantages compared to static models such as a higher modeling accuracy or the possibility to study other instability mechanisms not restricted only to the loss of equilibrium captured by static methods. QSS approximation also has drawbacks. One major disadvantage is the impossibility to deal with short-term instability scenarios. Therefore, if a long-term instability triggers a short-term instability for example, the software will not detect the short-term instability. Astre software operation and QSS approximation are widely described in [12] and [18].

Astre software can be used to determine security limits from margin computations. This possibility has been widely used during the Master's thesis work. Margin computation principle

is explained in [12] and [19]. Margin calculation[3] is an implementation of a combined secure operation limits determination and contingency filtering procedure. Secure operation limits is a type of security limit which indicates how far the system can be stressed prior to any contingency so that it will remain stable after the contingencies. It is easy to interpret as it refers to precontingency parameters that operators can observe or control. The principle of the margin calculation is binary search. The user determines a list of contingency, stopping criteria, a maximal consumption increase and a tolerance for the result Δ.

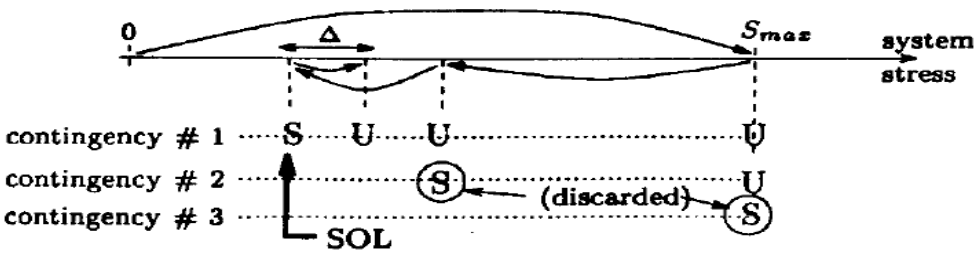


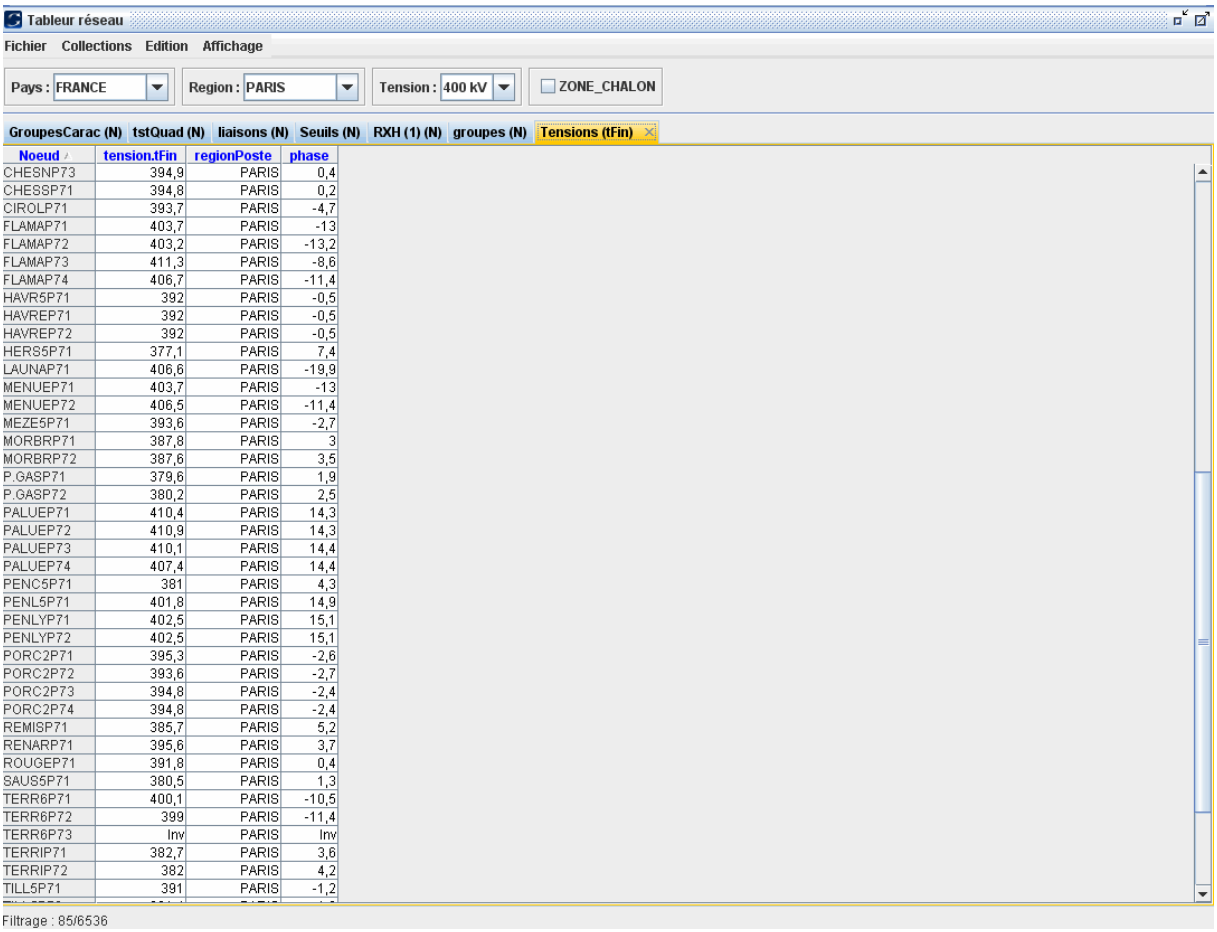
Figure 3.2 *Simultaneous binary search used for margin calculation* ***[12]***

For a list of contingency, the user can choose to have only the maximum consumption increase for the worst contingency (that is to make simultaneous binary search that is depicted in Figure 3.2) or the maximum consumption increase for all the disturbances.

A small modification has been done for this margin calculation recently in RTE. Instead of beginning with the maximum consumption increase, the search begins with the dynamic simulation without any stress. Indeed, a simulation that is stable in static calculations can be unstable dynamically without any stress and thus, it is recommended to check that the current system state is stable before checking that we can make a consumption increase.

It is also possible to use Astre software without using the margin calculation tool. In this case, the user can make dynamic simulations in two different steps[4]. He will first make a consumption increase and then simulate a disturbance for example. Therefore Astre software allows the user to see the results and the effects of the consumption increase and the disturbance separately. When the user makes classical dynamic simulations, it is possible to plot figures or to see results in a table format (for example, a table with the voltage values on the 400 kV network of an area such as in Figure 3.3).

[3] As said in the abbreviations and notations part, margin calculation and margin computation have been used interchangeably in this report.
[4] Classical dynamic simulations will refer to dynamic simulations made in two different steps later on in the report.



Noeud	tension.tFin	regionPoste	phase
CHESNP73	394,9	PARIS	0,4
CHESSP71	394,8	PARIS	0,2
CIROLP71	393,7	PARIS	-4,7
FLAMAP71	403,7	PARIS	-13
FLAMAP72	403,2	PARIS	-13,2
FLAMAP73	411,3	PARIS	-8,6
FLAMAP74	406,7	PARIS	-11,4
HAVR5P71	392	PARIS	-0,5
HAVREP71	392	PARIS	-0,5
HAVREP72	392	PARIS	-0,5
HERS5P71	377,1	PARIS	7,4
LAUNAP71	406,6	PARIS	-19,9
MENUEP71	403,7	PARIS	-13
MENUEP72	406,5	PARIS	-11,4
MEZE5P71	393,6	PARIS	-2,7
MORBRP71	387,8	PARIS	3
MORBRP72	387,6	PARIS	3,5
P.GASP71	379,6	PARIS	1,9
P.GASP72	380,2	PARIS	2,5
PALUEP71	410,4	PARIS	14,3
PALUEP72	410,9	PARIS	14,3
PALUEP73	410,1	PARIS	14,4
PALUEP74	407,4	PARIS	14,4
PENC5P71	381	PARIS	4,3
PENL5P71	401,8	PARIS	14,9
PENLYP71	402,5	PARIS	15,1
PENLYP72	402,5	PARIS	15,1
PORC2P71	395,3	PARIS	-2,6
PORC2P72	393,6	PARIS	-2,7
PORC2P73	394,8	PARIS	-2,4
PORC2P74	394,8	PARIS	-2,4
REMISP71	385,7	PARIS	5,2
RENARP71	395,6	PARIS	3,7
ROUGEP71	391,8	PARIS	0,4
SAUS5P71	380,5	PARIS	1,3
TERR6P71	400,1	PARIS	-10,5
TERR6P72	399	PARIS	-11,4
TERR6P73	Inv	PARIS	Inv
TERRIP71	382,7	PARIS	3,6
TERRIP72	382	PARIS	4,2
TILL5P71	391	PARIS	-1,2

Figure 3.3 *Example of table from Astre software*

The last point that will be mentioned regarding Astre software is its database. Astre software is used in operational context and in provisional studies by a lot of engineers. They all use the same version of Astre software with the same data base and the same functionalities (this version is host in distant servers). However, in Versailles, we have a local version of Convergence software and Astre software in order to make tests and validations for the evolutions before they are installed in operational context. It is then possible to try different changes on the database and to measure their impact. This opportunity is worth mentioning because changes on the database have been done during the Master's thesis work and have been tested on the local version of Convergence software. The database includes information about the generators limitations and maximum powers or the time constant between two tap changes for LTCs for example.

The most relevant aspects of Convergence software for the Master's thesis have been presented in order to have a better understanding of this tool. The other tool used during the work, Eurostag software, is described in the next section.

3.1.2 EUROSTAG SOFTWARE

Eurostag is a tool developed by RTE and Tractebel. It allows the user to make accurate dynamic simulations that are suitable for short-term stability studies, particularly rotor angle stability studies. However, it can also be used for voltage stability studies when it is necessary to have a time step lower than 10 seconds (Astre software time-step).
Eurostag software can make load flow simulations as well as dynamic simulations. The simulation starts with the load flow calculation: the software takes as input a .ech file containing active and reactive productions at the buses, lines and their characteristics, transformers and loads. Once the load flow has converged, the user can make dynamic simulations: dynamic data are described in a .dta file with for instance the machines and their regulators, the dynamic behavior of the loads or the tap-changers characteristics. The events that must be simulated are described in a .seq file. The user can simulate any kind of disturbance, consumption variations on a node or an area, manual blocking of LTCs and many other events. There is a visualization tool to display simulations results as well as to plot curves.

The major advantage of Eurostag software is its time step adaptation during dynamic simulations. This time-step varies during a simulation between a minimum and a maximum value, depending on the frequency of the variations in the system. For example, when there is an oscillation in the system, the time-step will decrease in order to capture this oscillation whereas if the system is finding an equilibrium point, the time step will increase. Another example is a case where a consumption increase is first made with the LTCs acting then the system finds a new equilibrium point and finally a disturbance is simulated after blocking the LTCs (that is the simulations scheme used for the LSD new activation point assessment). In this case, the time-step will increase after the stabilization following the initialization of the system. It will decrease during the consumption increase and then increases when the system state reaches a new equilibrium point. The time-step will decrease after the disturbance and will finally increase if the system state is stable. Figure 3.4 illustrates the example explained in the previous sentences.

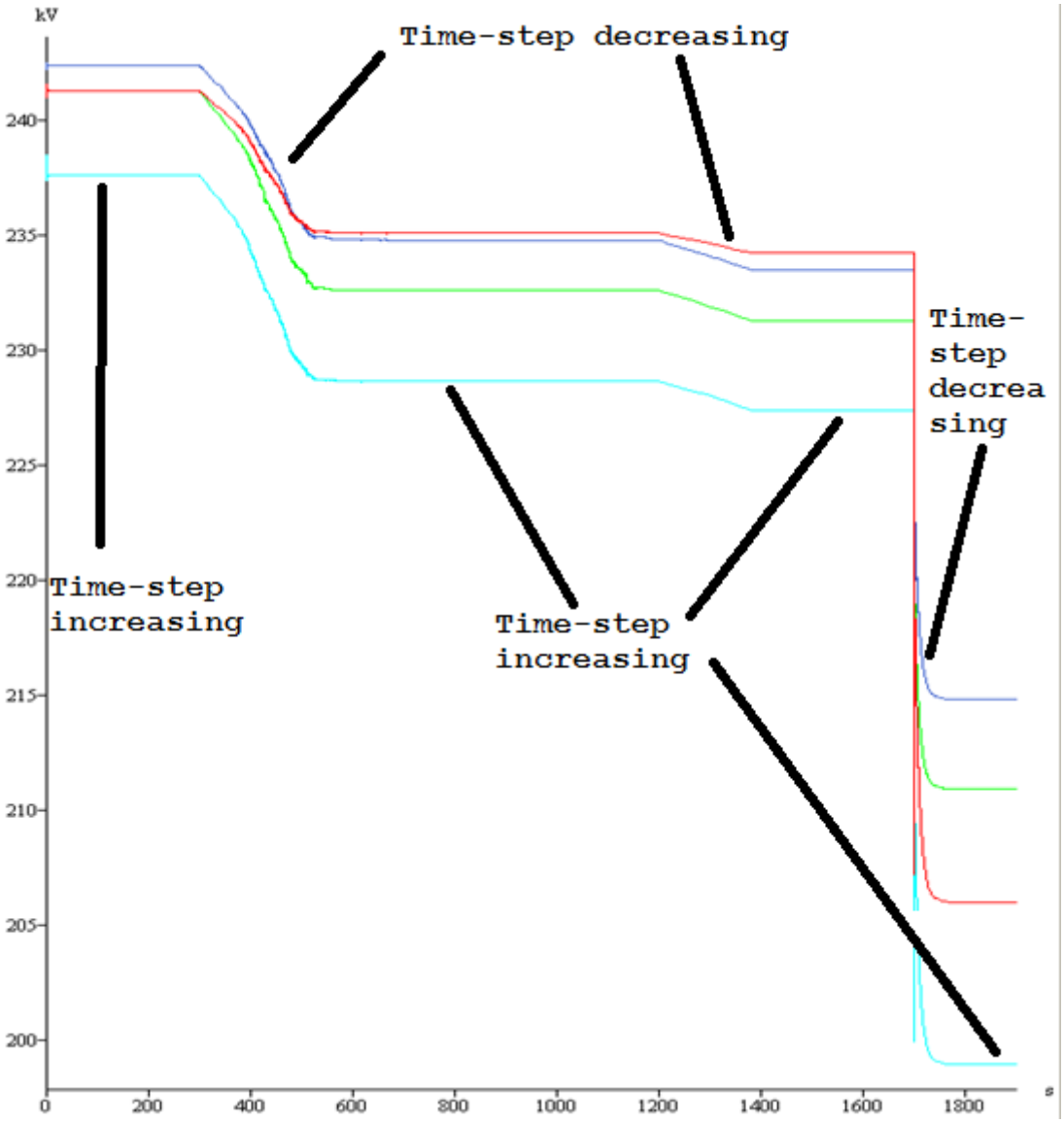


Figure 3.4 *Time-step adaptation*

As mentioned earlier, Eurostag software was developed for rotor angle stability but can also be used for voltage stability studies thanks to additional software developments. Eurostag software allows the user to adapt the files and the simulations to its needs. For example, he can make simulations with or without LTCs or add undervoltage protection scheme and custom automata.

After the presentation of the software used during the Master's thesis work, we will introduce the methodologies for the search of new static criteria and the determination of the new activation consumption level for LSD.

3.2 METHODOLOGIES

3.2.1 STATIC CRITERIA DETERMINATION

The purpose of static criteria is, as presented in chapter 2, to distinguish acceptable system states from undesirable ones. A static criterion is a secure operation limits tool used from week-ahead simulations to quasi real-time simulations that says if a system state is acceptable or not. And if not, countermeasures as the starting of new power plants or a load reduction are taken.

As a result, these criteria must have the following characteristics:

- They must be representative of a maximum of low voltage crisis system states.
- They must be conservative: that is to say they must detect all the undesirable system states. There should not be any critical mistake[5] in order to assure the voltage security of the network.
- They must limit the number of false alarms leading to the starting-up of power plants or other remedial actions and so reduce costs for the company.

Figure 3.5 depicts the characteristics presented above.

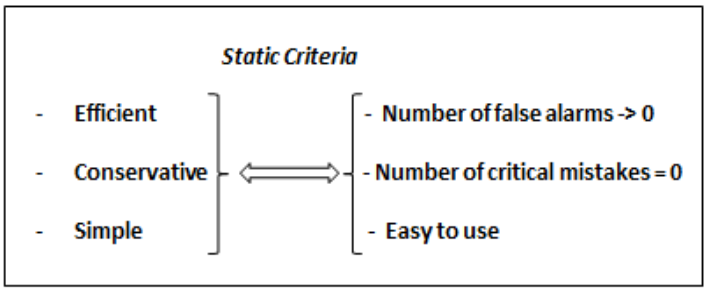


Figure 3.5 *Static criteria characteristics*

Simple criteria refer to criteria that are easy to use. For example, a simple criterion is V(Node A) > 383 kV whereas on the contrary, $\frac{\sum_{Area\ nodes} V}{nb\ of\ nodes} > 383\ kV$ is not simple.

The construction of these criteria is done in off-line studies in different steps:

- Define stopping criteria for margin computations (presented in the previous section)
- Define the list of contingencies and the system states used for the simulations.
- Split the system states between acceptable and undesirable with dynamics simulations and margin computation.
- Run load-flow calculations for the worst undesirable system state for the entire list of contingencies.
- Note voltage values and other parameters such as reactive reserves after the load-flow calculations
- Build the criteria with these results.

[5] Detecting an undesirable system state as acceptable is a critical mistake whereas detecting an acceptable system state as undesirable is a false alarm. False alarms don't jeopardize the system security but lead to additional costs for the company. On the contrary, critical mistake jeopardize the system security because undesirable conditions are not detected.

The first step in a study is to define stopping criteria for margin computation and off-line dynamic studies. The second step is to determine a list of contingencies and a list of system states that will be used. These system states correspond to different days with different consumption levels and different network topologies for example. Determining these inputs will impact the criteria. Indeed, for example, different stopping criteria for margin computation will give different undesirable system states and thus different static criteria.

Once these inputs are set, the first set of simulations is a set of dynamic simulations. We use Astre software and margin computations to determine undesirable system states. Making these margin computations is a time-consuming task. Indeed, for a list of thirty contingencies and ten basic system states[6], the software has to run three hundred dichotomy searches.
Then, once we have characterized the undesirable system states, load-flow calculations will be run with Hades software. Only the undesirable system state corresponding to the worst contingency (known as the limiting disturbance) is kept for load-flow calculations. The worst contingency for margin computation is the contingency that accepts the lowest stress. Indeed, the voltage values after load flow calculations will be higher for the system state corresponding to the worst contingency because the consumption level is the lowest. At this point, we can summarize: for each basic system state and each disturbance, we have an undesirable system state characterized by a consumption increase compared to the basic system state. Then only the worst undesirable system state is kept and load flow calculations are made in order to note the resulting voltage, reactive reserves, etc. values. Finally, based on the results of these load flow calculations, static criteria are determined. Figure 3.6 demonstrates this principle and Table 3.1gives an example.

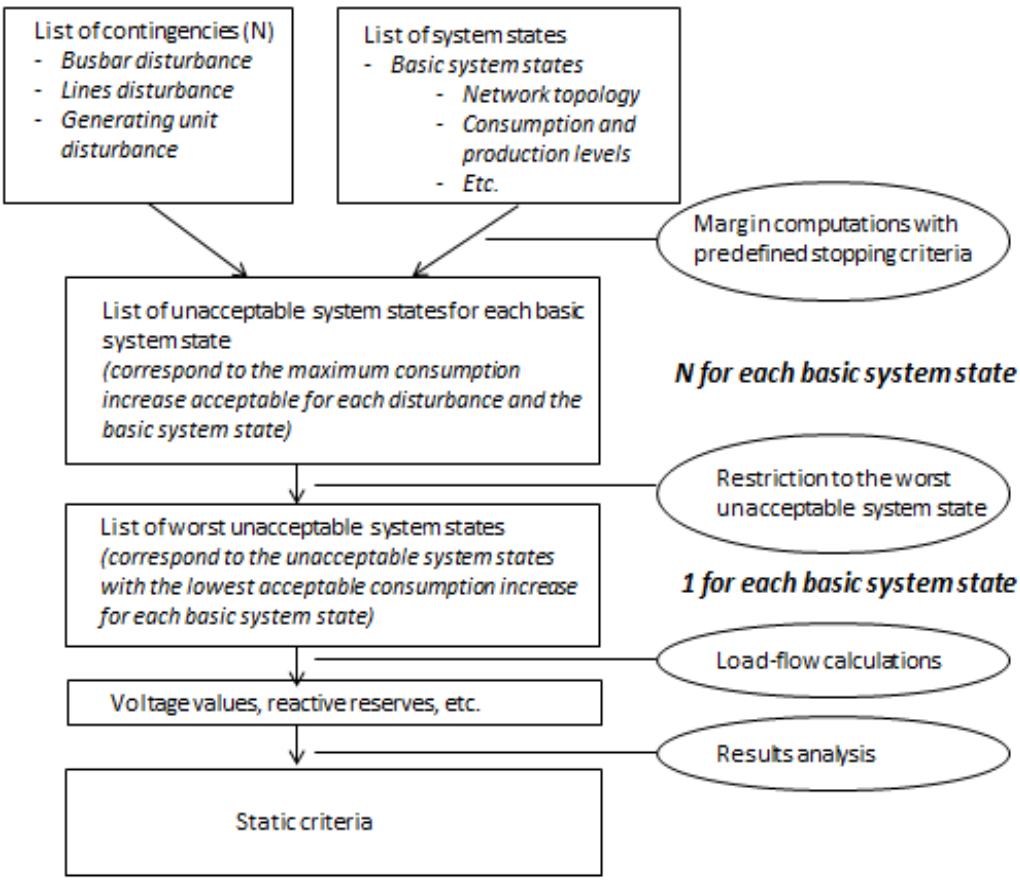


Figure 3.6 *Static criteria determination*

[6] A basic situation refers to a situation taken in the situations list. A basic situation corresponds to a particular situation with a consumption level, a network topology, etc.

Basic system state: *30th of January, with Chooz 2 generating unit unavailable*	
Contingencies	Undesirable system state
Busbar fault 1	*300 MW consumption increase*
Busbar fault 2	*500 MW consumption increase*
Busbar fault 3	*400 MW consumption increase*
Worst undesirable system state*: Basic system state + Busbar fault 1 + 300 MW consumption increase*	

Table 3.1 *Example for the three first steps of static criteria determination*

3.2.2 NEW CONSUMPTION LEVEL DETERMINATION FOR LSD GLOBAL MODE ACTIVATION

The aim of this study is to determine a new activation level for the LSD global mode by using dynamic simulations in Eurostag software on the most stressed system state from last winter. Consumption increases and losses of two generating units in the coal production center (as mentioned in 2.3.2.2, the global mode is designed to prevent a possible system collapse after this disturbance) are simulated and we see if the system is collapsing in the first ten to twenty seconds. Finally the activation level is equal to the first consumption level leading to system collapse minus a security margin.

The methodologies and the tools relevant for the achievement of the Master's thesis goals have been presented as well as the theoretical background for voltage stability as well. The next part will focus on case studies.

4 EXPERIMENTATIONS AND RESULTS

This chapter describes case studies and their results which can be divided into three parts. The first part deals with static criteria research and the switch to on-line dynamic simulations after results analysis, the second focuses on the work on the LSD and the third one on other experimentations led on the voltage stability topic.

4.1 WITHDRAWAL OF STATIC CRITERIA AND ASTRE DATABASE IMPROVEMENT

In this part, we will explain first for the North-East area and then for the East area (Figure 1.3) the process that has led us to give up static criteria and to replace them by on-line dynamic simulations. The improvement of Astre database resulting from this change is also presented. A chronological approach has been chosen in order to highlight the different steps of the reasoning leading to the final change.

4.1.1 NORTH-EAST AREA

4.1.1.1 PRESENTATION OF THE STUDIED AREA

The work on static criteria has begun with the North-East area. The network of this area is shown in Figure 4.1. This area is characterized by important power flows from North to South during voltage crisis. Indeed, during these periods, France is importing electricity from the Northern European countries (Germany, Belgium, and Netherland) in order to supply the Parisian area and to assure the balance between consumption and production. An important part of the power flow coming from these countries to Paris passes through the North-East area of the French network and therefore the power lines in this area are operated close to their limits during high consumption periods. The main production units of the North-East area are the nuclear units of Gravelines and Chooz.

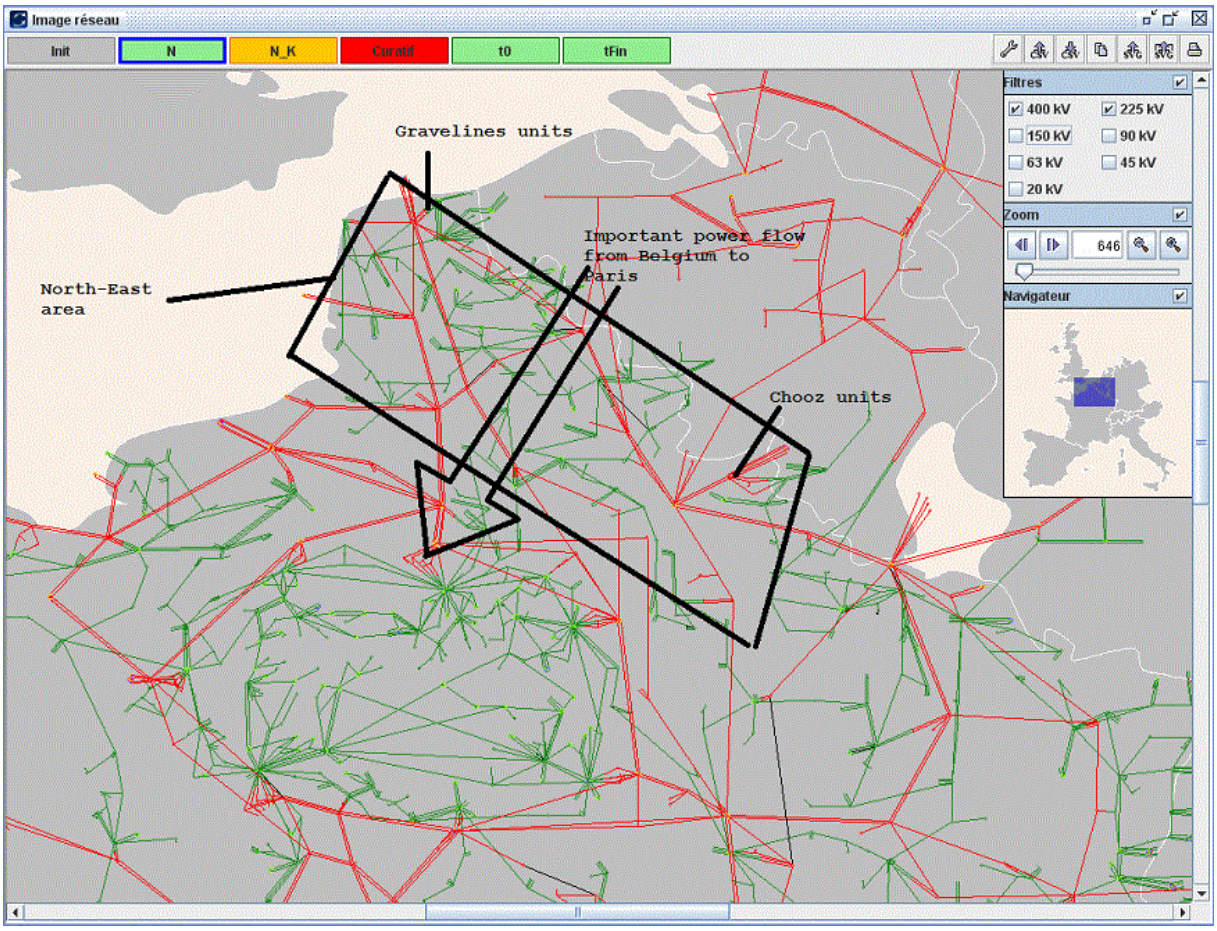


Figure 4.1 *North-East area*

There were two static criteria on this area in order to prevent the system collapse in this part of the network. These two criteria were located on the 400 kV network in two different nodes. However, there was the idea (this idea comes from the situations observed during the consumption peaks from last winter) among operational engineers that these criteria were no longer valid. These concerns could be summed up by two questions:

- Are the existing criteria still conservative and thus valid? Are they efficient?
- If not, is it possible to find new static criteria?

In order to answer these questions, the first step is to define stopping criteria for margin computations as well as the list of system states that we would use for the studies and the list of disturbances that would be simulated. After discussions with engineers from different entities and consultation of different RTE internal notes and RTE obligations, it has been decided that a system state will be undesirable if:

- During the dynamic simulation, the voltage value becomes lower than 0.8 U_n on the 400 kV or the 225 kV network
- At the end of the dynamic simulation, the voltage value becomes lower than 383 kV or 219 kV on the connecting points of nuclear power plants
- At the end of the dynamic simulation, there is a total amount of load higher than 300 MW with voltages lower than 0.8 U_n

- At the end of the dynamic simulation, the voltage is lower than 200 kV on a 225 kV node
- The dynamic simulation diverges. In this case, a dynamic simulation in two steps will be done. First a consumption increase is simulated and then the disturbance is done to see if the divergence is provoked by a real problem or by a model problem.

Regarding the list of contingencies, as static criteria aim is to ensure that the system is satisfying the (N-1) criterion, it had been chosen to simulate all the busbar faults of the area for the 400 kV buses and busbar faults on some nodes of the Normandie-Paris area.
We chose the system states from the coldest days from last winter as basic system states – that is the days between the 30th of January and the 10th of February (the peak consumption in France was reached on the 8th of February [19]). For each of these days, there were one or two available snapshots. A snapshot is a file corresponding to the real system state observed on the network at a precise hour (generally during the morning or the evening peak consumption). These snapshots are captured by sensors installed on the network giving the voltage values on the nodes, the active and reactive power flows, etc. These snapshots can be used in Convergence software after an automatic treatment correcting the measurements errors.

4.1.1.2 FIRST SET OF SIMULATIONS AND RESULTS

The next step was to make the first set of simulations. For each of the basic system states (i.e. each snapshot), margin computations were carried out for the full list of contingency with the stopping criteria presented in the previous section. The stress for the margin calculations were an active and reactive power consumption increase in the North-East area. In order to cover a wider range of possible system states, additional system states have been derived from real basic system states by disconnecting one nuclear unit in Gravelines or Chooz before the system stress. The margin computations have allowed us to recover the list of undesirable system states and then the list of the worst undesirable system states.
Active and reactive power increases were statically done in order to convert the basic snapshots into the worst undesirable system states. Then all the contingencies were simulated with Hades software and the resulting voltage values after the disturbances were noted. The first set of results have been got and analyzed in order to answer the questions presented in the previous section. A representative sample of these results is presented in Table 4.1, Figure 4.2, Figure 4.3 and Figure 4.4.

Basic system states			
Undesirable system states	Max. Cons. Increase	U (Node 1)	U (Node 2)
30/01	1474 MW	381,1	377,0
30/01 without Chooz 2	1458 MW	384,6	376,9
30/01 without Gravelines 6	1304 MW	378,0	379,0
31/01 without Gravelines 6	1182 MW	378,7	376,2
31/01 without Chooz 2	1846 MW	379,7	370,0
02/02 without Chooz 2	2000 MW	381,7	380,0
08/02	529 MW	387,8	374,9
08/02 without Gravelines 6	474 MW	385,5	376,2

A system state is considered acceptable if U (Node 1) ≥ 380 kV and U (Node 2) ≥ 370 kV. Red values correspond to critical mistakes and black ones to correctly identified undesirable system states.
Chooz 2 and Gravelines 6 are nuclear generating units.

Table 4.1 *Example of results from the first set of simulations*

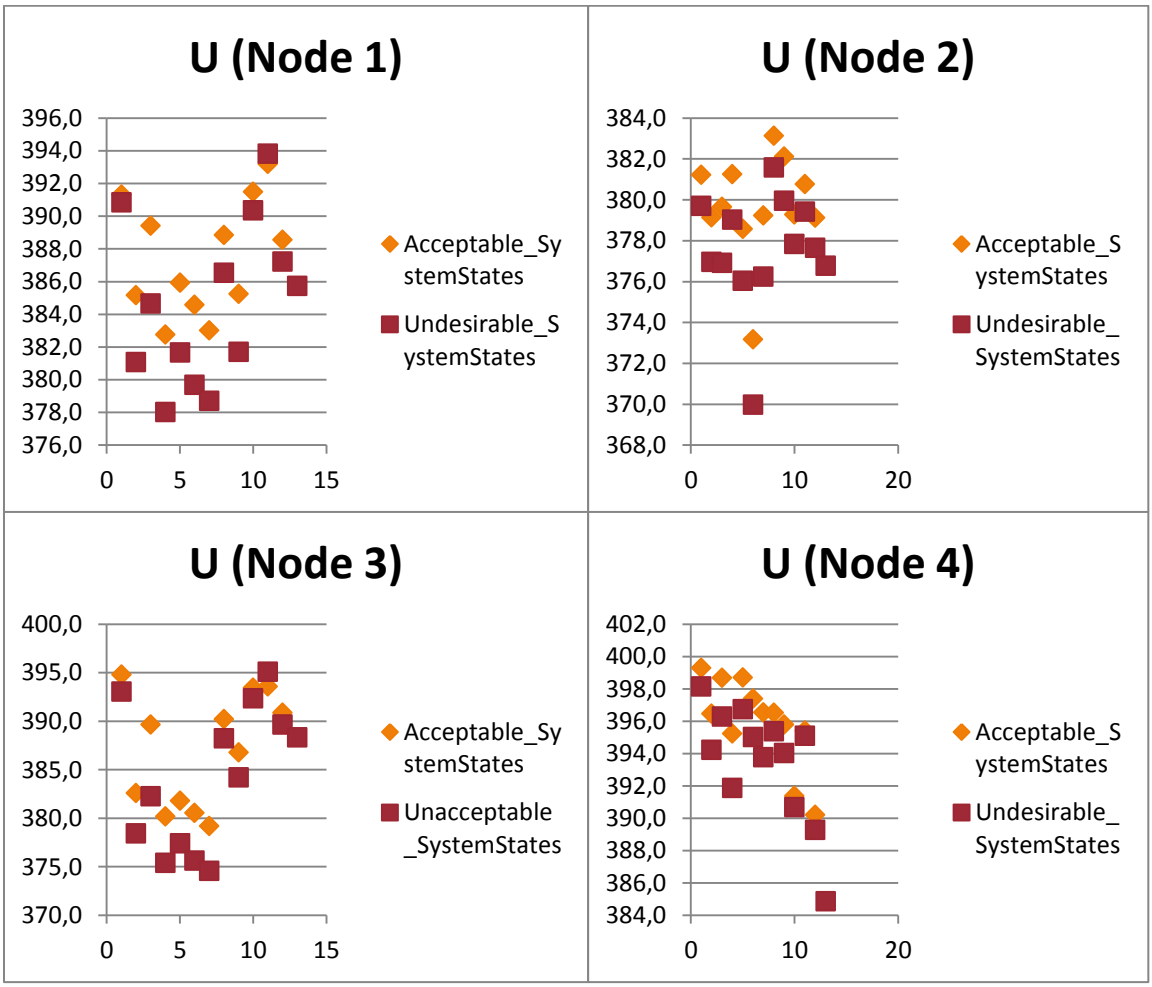


Figure 4.2 *Voltages on one node for acceptable and undesirable system states*

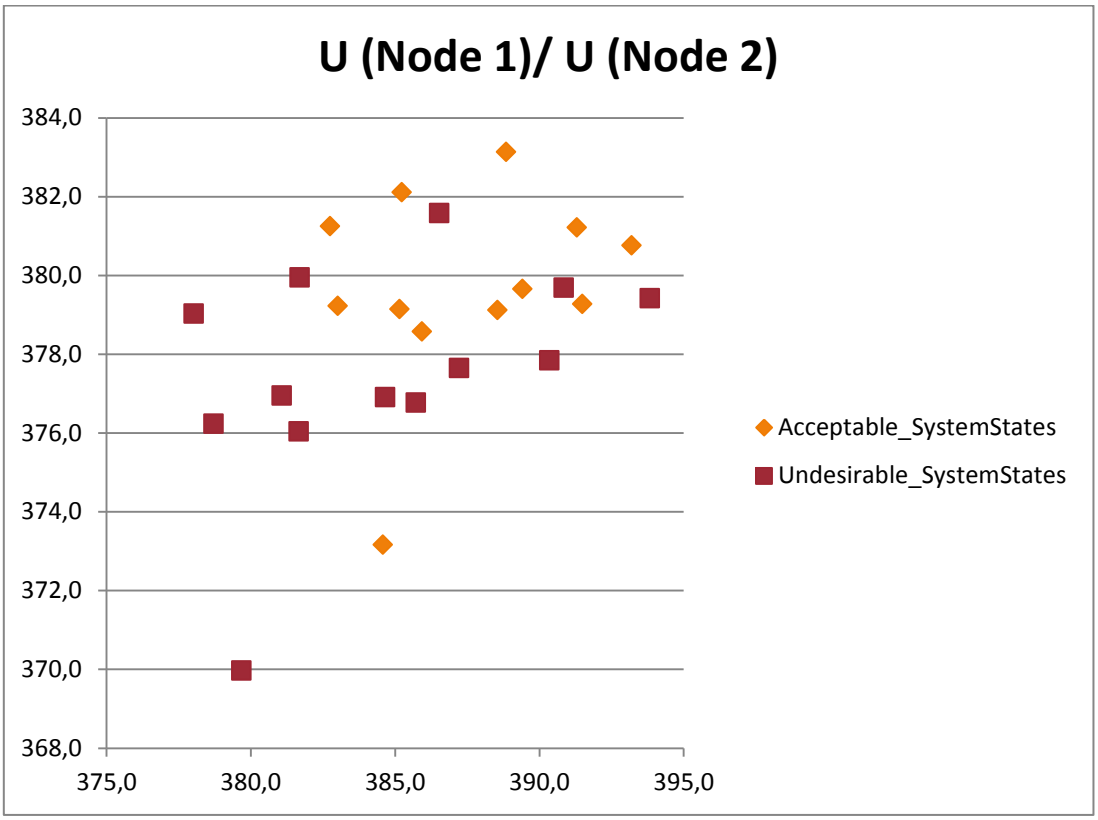


Figure 4.3 *Voltages for two nodes for acceptable and undesirable system states*

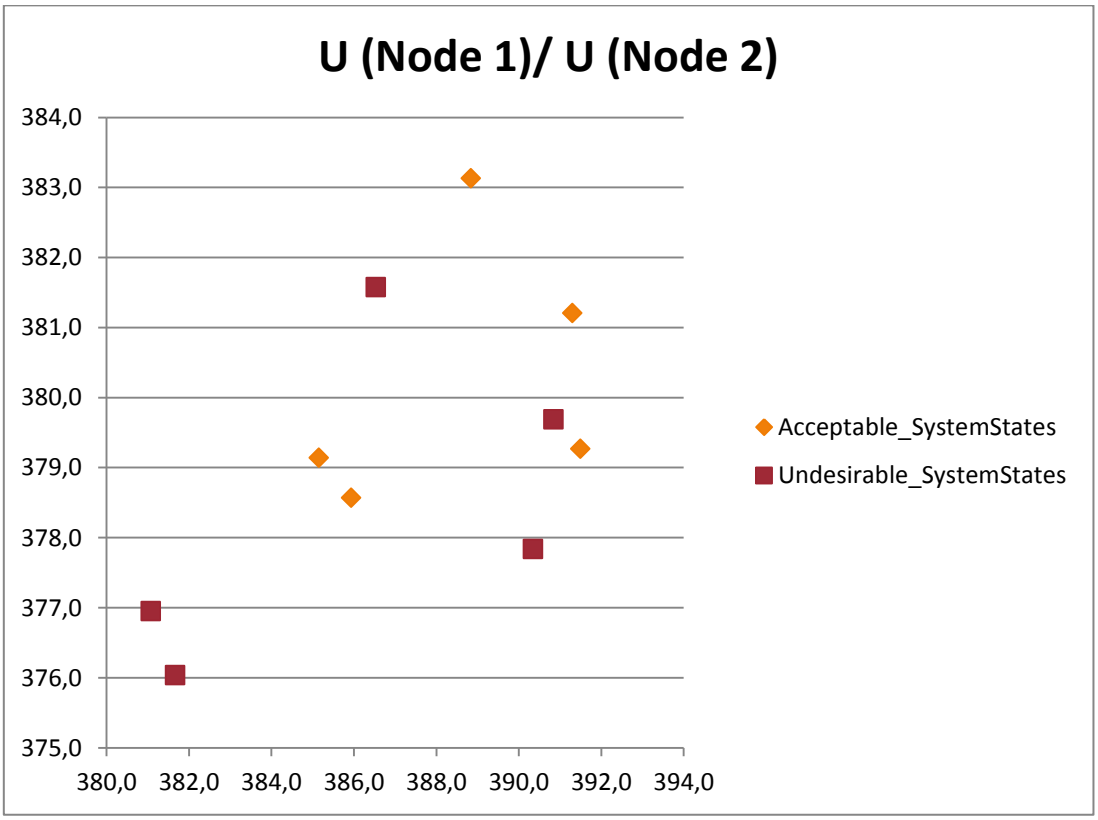


Figure 4.4 *Voltages for the same nodes* as ***Figure 4.3*** *but only for system states without unavailability of generating unit*

The analysis of these results led to the following conclusions, explained in the next paragraph:

- The existing criteria were no longer conservative [7]and so couldn't be kept (they don't detect all the undesirable system states as undesirable).
- It was difficult to find new efficient criteria (an efficient criterion is a criterion that doesn't detect acceptable system state as undesirable).
- In most cases, the worst contingency was the same busbar fault and led to the entire system collapse and not only a collapse limited to the North-East area.

As it is noticeable on the above Table 4.1, the voltage is, for undesirable system states, higher than the existing criterion. For the first criterion, it is the case for the 30th of January with or without Chooz 2 (nuclear unit), for the 2nd of February without Chooz 2 and for the 8th of February morning with or without Gravelines 6. For the second criterion, only one undesirable system state is detected as undesirable (31st of January without Chooz 2). By way of consequence, it was impossible to keep the existing criteria that didn't detect all the undesirable conditions as undesirable. The second conclusion is highlighted by the Table 4.1 and the Figure 4.2, Figure 4.3 and Figure 4.4. In Table 4.1, we observe that, in order to keep the criterion on the same node, the lowest acceptable voltage values should have been considerably increased (up to 388 kV or 380 kV). However, in Figure 4.2, we can see that quite a few acceptable system states would be situated under these new limits: this criterion would be far too restrictive. We also tried with voltage values on other nodes and with combination of voltage values - as can be seen on the Figure 4.2 for example – but it was impossible to build a criterion that would be conservative and efficient at the same time. The third conclusion had played a very important role in the change of direction taken later on. What we also noticed in the results of the simulations was that the margin computation worst contingency (or the disturbance accepting the lowest consumption increase before hitting the margin computation stopping criteria) was in most of the case the same. This disturbance was a busbar fault on a node not located in the North-East area but close to it. It led to a collapse of the whole system (named 'global system collapse') with the nodes of the North of the Parisian area and the South of the North-East area with the lowest values. A global system collapse is the contrary of a local system collapse: a global system collapse involves a great number of nodes and several areas whereas a local system collapse is a system collapse on a precise part of an area. The fact that the worst contingency led to global system collapse is crucial because it implies that the problem is a global problem and static criteria defined for each area are designed mainly for local problems. Due to these conclusions – impossibility to find simple, efficient and conservative criteria, global problematic involving the whole system instead of local issue – we decided to give up static criteria and to replace them by on-line dynamic simulations, which was a major change in my Master's thesis aim.

4.1.1.3 THE PERSPECTIVE CHANGE

This part is devoted to the analysis of the consequences and the reasons of this major change (i.e. giving up static criteria and replacing them by on-line dynamic simulations).

There are two main reasons explaining this complete upheaval of the perspective as mentioned in the previous section. Indeed, we established that it was impossible to find simple, efficient and conservative criteria ant that the main issue was a global issue and not a local one. The underlying certainty resulting from these observations was that the approach by areas and static criteria were no longer valid in our current grid. RTE engineers already had this idea in mind one year ago when studies were made on four areas of the French network (West, Normandie-

[7] See 3.2.1 for conservative definition.

Paris, South West and South East areas) to give up static criteria and replace them by on-line dynamic simulations. However, for three areas (North-East, East and Rhône-Alpes Auvergne areas), RTE decided to keep static criteria for the time being. This choice was motivated by the fact that the neighboring networks model was not good enough in Convergence software. However, the first set of results obtained during my study on the North-East area spotlighted the necessity to give up static criteria and to adopt on-line dynamic simulations. As a consequence, this time, RTE engineers took the decision to give up static criteria and to replace them by on-line dynamic simulations. This change had three prerequisites:

- Improve the model for neighboring countries networks and validate these improvements
- Check that, by giving up static criteria, no local problems only detected by static criteria would be missed
- Give the worst contingencies (for nodes located in the North-East area) that must be simulated in on-line simulations

The perspective change is shown in Figure 4.5.

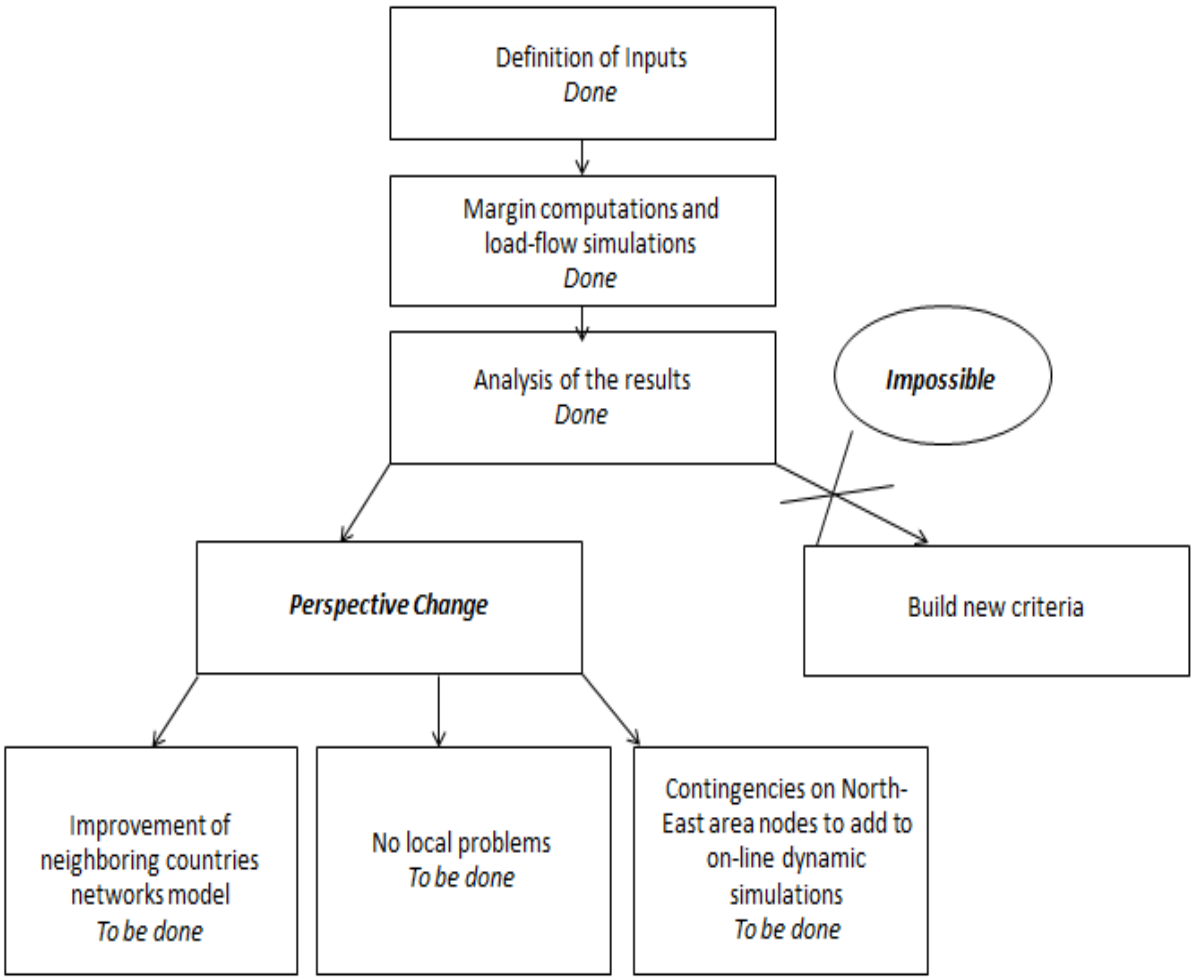


Figure 4.5 *Perspective change*

4.1.1.4 IMPROVEMENT OF NEIGHBORING COUNTRIES NETWORKS MODEL

In order to move from static criteria to on-line dynamic simulations, it was necessary to improve the Belgian and German generators dynamic model. To understand that part, neighboring countries networks model currently used must be introduced. Today, for on-line studies, RTE utilized the whole French network (transmission lines from 63 kV lines to 400 kV lines) and "un anneau de garde" for the neighboring countries network (we will call it the "*foreign belt*" in English in this report). This "*foreign belt*" is a partial representation of the EHV network of the France neighboring countries (Belgium, Germany, Switzerland, Italy, Netherland, Austria and Spain). In this "*foreign belt*", not all the nodes are represented and there are no more than five nodes between the furthest node represented in the "*foreign belt*" and a French node. For example, the German network is limited to some nodes in the Western part of Germany and there is only one node in Austria. The "*foreign belt*" is updated from time to time (typically each five years). This "*foreign belt*" is a way of taking into account the behavior of the neighboring countries networks and to have a better accuracy in the results for dynamic studies done in areas close to borders. Figure 4.6 displays a partial view of this "*foreign belt*".

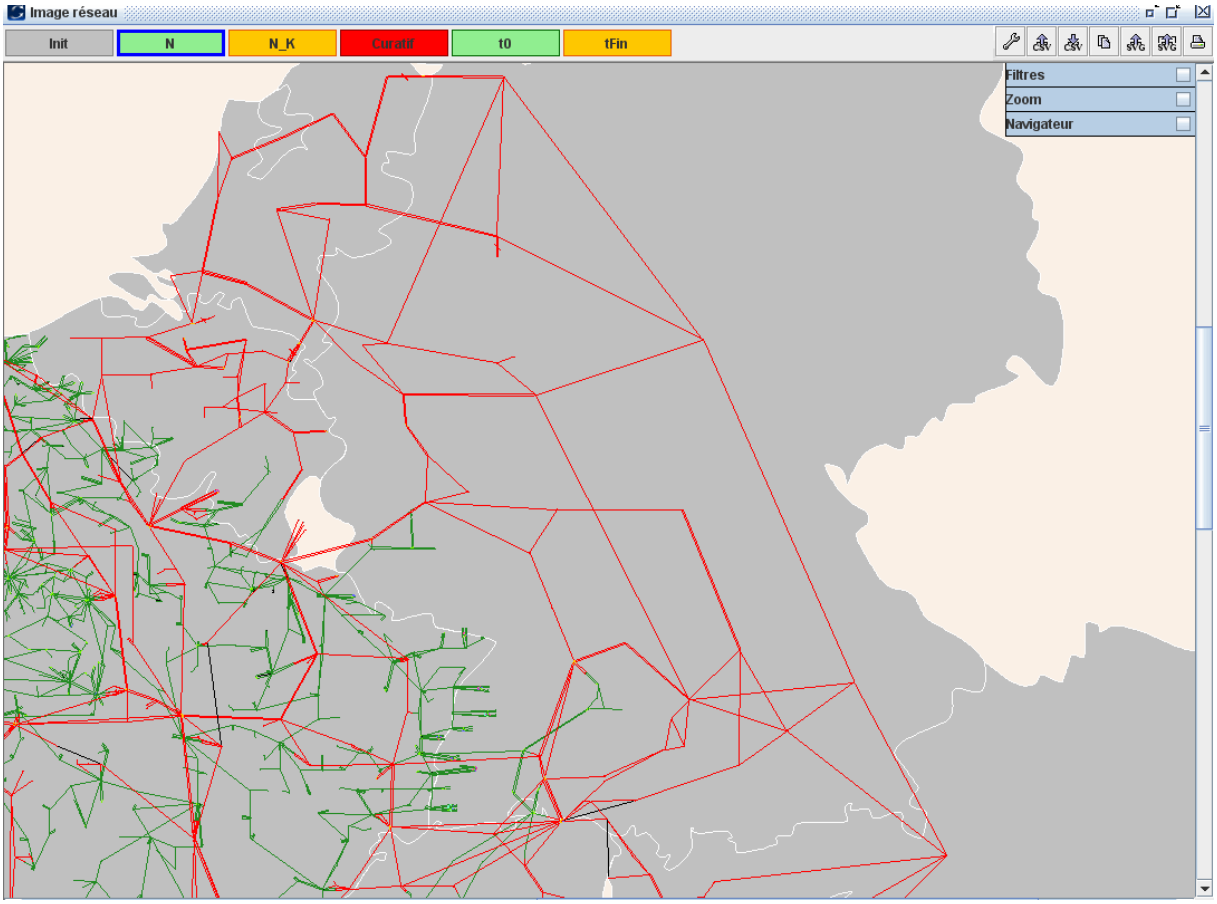


Figure 4.6 *"Foreign belt" illustration*

However, this model had a major drawback: generators in the "*foreign belt*" didn't have any dynamic data so they could produce an infinite quantity of reactive power thus keeping high voltage values on the Belgian and German grids even when the French voltage plan was

degraded. This question is important for dynamic simulations because the reactive power production can make a peak at a time step and then return to normal values, hiding the problem to the user.
Static criteria are less sensitive to the "*foreign belt*" model than dynamic simulations. Indeed, dynamic simulations use the dynamic database and split system states between acceptable and undesirable system states based on the results from these dynamic simulations. The impact of dynamic database on static criteria can be neglected because the dynamic database only influences one step in the overall static criteria determination process.

The decision was thus taken to build dynamic data for some generators of the "*foreign belt*". Some generators of the "*foreign belt*" model are fictitious generators added in the "*foreign belt*" to allow convergence in Astre simulations. For these generators, no dynamic data had been added. The list of these generators was given by operational engineers familiar with the network and the models. For the other generators, dynamic data was added and therefore their active and reactive capabilities were limited.
The problem was to choose what data should be put in the database because we didn't have the characteristics of the units. In order to put correct values, we used the Day-Ahead Consumption Forecast (DACF) files supplied by each TSO to Coreso (a transnational agency in charge of the supervision of the interconnections between the Central-Western Europe countries). In these files, the different TSOs put their consumption and production previsions for the day-after and send them to Coreso, which makes them available for all the TSOs. Tests are currently led in RTE in order to have an automatic process for the use of these files instead of the "*foreign belt*" for day-ahead studies. Nevertheless, what interested us there was the fact that these files contained the characteristics of the foreign generators. However, there were conflicts between the *"foreign belt"* and the DACF files such as generator names. Moreover, some generator units had been put together in the "*foreign belt*" and the number of generating units present in the DACF can change from one file to another. It was thus necessary to establish a correspondence between the DACF generating units and the "*foreign belt*" generating units to build correct dynamic data. By looking on different DACF files and comparing my conclusions with information given by the CNES and Coreso, it was possible to build dynamic data for the *"foreign belt"* generating units.
Once the data was recovered, the next step has been the modification of Astre database. Then, before deploying this database in operational context, it was necessary to see if there were no software problems due to the modification of the database. Tests were done first in Versailles and then in CNES. In Versailles, the tests were done on sixteen system states (four basic system states and four possible disturbances) of the beginning of February. There were no problems of software divergence observed. The maximum difference obtained for margin computations between the old and the new modified database was of 100 MW. Out of a total of sixteen different simulations, the maximum consumption increase was:

- Seven times identical for the two databases
- Nine times 50 MW lower for the new modified database (i.e. for the improved model for neighboring countries networks)
- Two times 100 MW lower for the new modified database

It is logical that the margin computation should give lower maximum consumption increases with the new database because the "*foreign belt*" was no longer kept at high voltage values by its producing units.

Astre database was improved with the addition of dynamic data for the units of the "*foreign belt*", which gave lower maximum acceptable stress and didn't lead to divergence problems for the software. This new database is now used in operational context. The next challenge is to check the absence of local voltage instability.

4.1.1.5 ABSENCE OF LOCAL VOLTAGE ISSUE AT REASONABLE CONSUMPTION LEVEL AND INTERESTING DISTURBANCES FOR THE ON-LINE DYNAMIC SIMULATIONS

In order to validate the withdrawal of static criteria and their replacement by on-line dynamic simulations, it was necessary to prove that there was no local voltage instability on the North-East area only detected by static criteria. The simulations done to build new static criteria gave the maximum consumption increase for each busbar disturbance and each basic system state by margin computations. These results were used to prove the absence of local voltage instability.
For some busbar disturbances, even with a considerable consumption increase (the maximum consumption increase was 2 000 MW), the system remained stable and didn't hit the stopping criteria during margin computation. For others, the margin calculation detected a maximum acceptable consumption increase. For these system states, the consumption increase and the disturbance were simulated in two steps. In most cases, there was a global system collapse always in the same zone (North of Parisian area and South of North-East area). There was only one busbar fault that induced a voltage decrease on only three nodes surrounding it where the voltage was lower than 200 kV at the end of the simulation for a quite small consumption increase. However, there is no possible corrective action to increase the voltage value in these nodes (no units at proximity, no capacitors to switch on, etc.). Moreover, the problem had limited consequences and the three nodes are in antenna. As a result, we considered that this case was not important and that it was possible to switch to on-line dynamic simulations.

We also wanted to know which disturbances in the North-East area must be simulated in on-line studies. Indeed, on-line dynamic simulations with Astre software and margin computations are a time-consuming task even with the improvements in computational capacities and the QSS approximation so it is not practical to simulate all the disturbances in on-line dynamic simulations contrary to static simulations. Thus we compared the maximum consumption increase tolerable for disturbance in the North-East area with the worst contingencies of the Normandie-Paris area leading to global system collapse in the Northern part of the Parisian area and the South of the North-East area. These contingencies are the loss of a nuclear unit in two of the Paris-Normandie area unit. As the main characteristic of the North-East area is a high amount of power flow going through it from Belgium to Paris, we made consumption increases on the North area and we also tried to increase consumption in Paris-Normandie and West areas. The conclusions from these simulations were:

- There were two disturbances that led to global system collapse for a consumption increase similar to the ones got for the worst contingencies of the Normandie-Paris area. It was the case with consumption increase on the North-East area and with consumption increases on West and Normandie-Paris areas.
- The maximum consumption increase tolerable for all these disturbances is lower when the consumption increase is made on West and Normandie-Paris areas rather than on North-East areas.

There is a link between these two conclusions. Both of them are due to the power flow increase from North to South during voltage crisis in order to satisfy demand from the Parisian area. All the North-South lines are operated close to their limits so the loss of one of these lines will induce higher power flows on the remaining lines and then the system's operation point can move towards the bottom of the PV curves. As the reactive reserves are low in the area and the LTCs many, there is a global system collapse. The two disturbances in the North-East area are a (N-1) highly loaded line and a busbar fault with the loss of a North-South axis. That characteristic of the system states explains that the maximum consumption increase is lower for stress done on West and Normandie-Paris areas compared to stress done on North-East area.

Consumption increase in the North-East area will decrease the power flows from North to South. However, it could be interesting to make a consumption stress on Western, Normandie-Paris and North-East areas together.

The three points that had to be validated for the evolution from static criteria to on-line dynamic simulations had been checked and so the evolution had become real and no static criteria will be used this winter for the North-East area.

4.1.1.6 SENSITIVITY STUDIES

In order to complete the study on the North-East area, several sensitivity studies were realized. In these studies, generating units were disconnected, power transfers between the countries modified and LTCs blocked before the disturbance.
Unavailability of generating units on the North part of the North-East area (such as Gravelines or Chooz nuclear generator for example) induced an increase of the maximum acceptable consumption increase for the worst contingencies. This result can be explained by the fact that the North-South power flows were decreased due to the compensation model used. Indeed, when a generator was disconnected, its production had to be produced by other units and in Astre software, this lack of production is compensated by the same amount of production increase spreading equally between all the French units.
Unavailability of generating units close to the North of the Parisian area was unfavorable for the maximum acceptable consumption increase because these generators were producing reactive power that was necessary for the voltage stability of the area. The loss of one of these units didn't decrease the power flows from North to South and deprived the zone from a reactive input.
Modifications of the power transfers between the countries were also studied. For example, a decrease of the imports from Belgium compensated by an increase of the imports from Spain allowed to gain quite an important margin for the maximum acceptable consumption increase (for 100 MW of decrease of the imports from Belgium, it was possible to increase the maximum acceptable consumption increase by 40 MW).
The last simulations done were made with tap changer position blocking before the disturbance in the Northern Parisian area. Thanks to that preventive blocking, it was possible to increase the maximum acceptable consumption increase by 300 MW on average for the most stressed system states.
These sensitivity studies gave an idea of the impact and the weight of the production units, the imports and the LTCs in the system collapse phenomenon observed.

4.1.1.7 CONCLUSION

The initial goal of this part of the Master's thesis work was to discuss the efficiency of the existing static criteria and if they were proved to be no longer valid nor conservative, new static criteria should be determined. Nevertheless, the first results spotlighted the fact that existing criteria were not conservative (they didn't detect all the undesirable system states) and the difficulty to find new ones. This observation along with the remark that the worst contingency induced a global system collapse led to the withdrawal of static criteria and the switch to on-line dynamic simulations. To be validated, this change required an improvement of Astre database by the addition of dynamic data for generators of the "*foreign belt*". We showed that there were no local problems on the North-East area that can only be detected by static criteria. It was then necessary to determine which disturbances of the North-East area must be added to the list of disturbances that are simulated in on-line dynamic simulations. From an initial objective of updating the static criteria, the goal of the work has evolved with the different results obtained and the reflections that they have induced to the withdrawal of the static criteria and the use of

on-line dynamic simulations instead after an improvement of Astre database and some verifications and validations steps.

4.1.2 EAST AREA

4.1.2.1 PRESENTATION OF THE STUDIED AREA

After the different results obtained and the experience of the study for the North-East static criteria, the study for the East area was conducted a bit differently. RTE engineers had the conviction that the existing static criterion on the East area needed to be improved and that there was only one zone that could be subject to local voltage problems at the eastern side of the East area (the existing criterion couldn't detect this problem due to its location). So instead of searching for a new static criterion, we started by searching for local system collapses. The goal was to see if static criteria were still need and if not, to suppress them.

The East area is a quite large area with different characteristics. For example, the western part of the East area, close to Paris (Mery/Boctois, etc.) is characterized by important power flows going to Paris and high consumption level. The eastern side of the East area, close to the German and Swiss boundaries, represents another zone with its own evolution as the south part of the East area which is strongly linked with the Rhone Alpes Auvergne area. There are three nuclear power plants in the East area: Cattenom, Fessenheim and Nogent. Figure 4.6 displays the East area network.

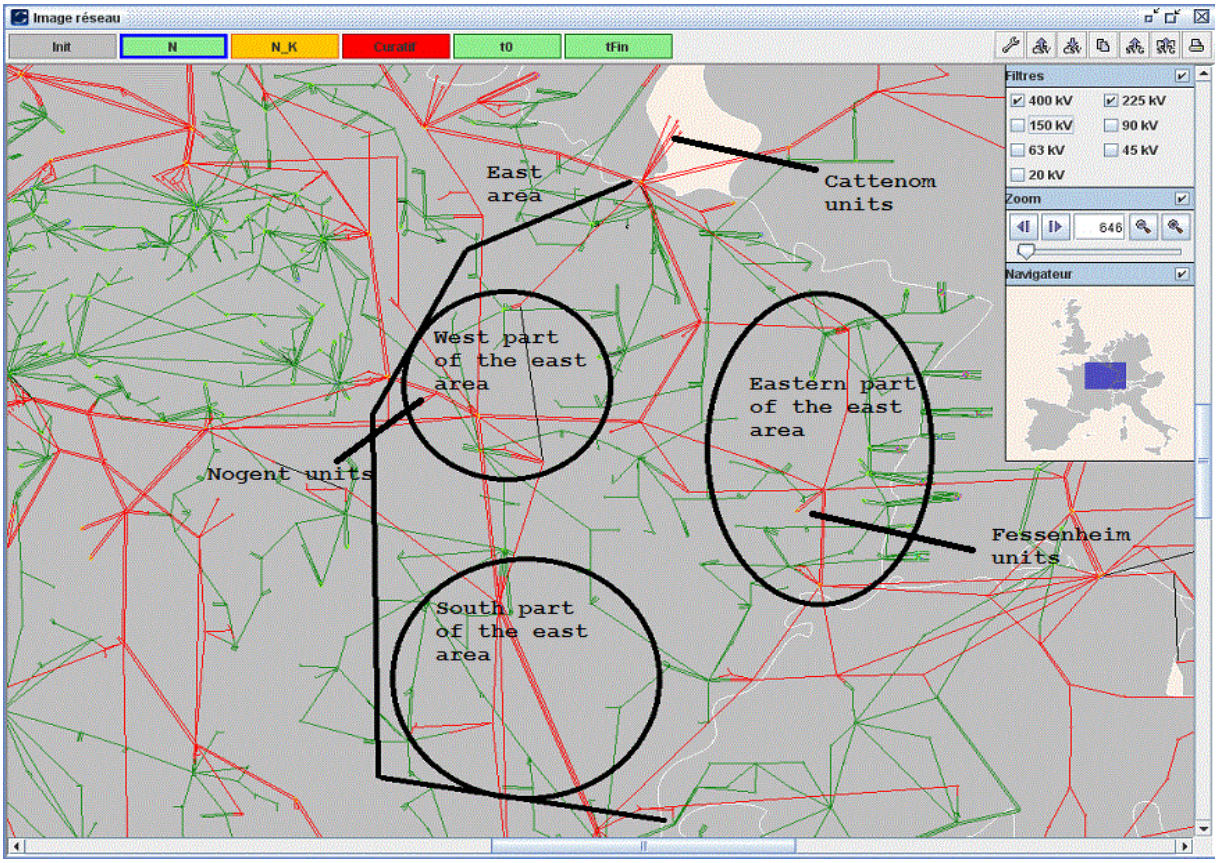


Figure 4.7 *East area*

4.1.2.2 ABSENCE OF LOCAL ISSUE

To search for local voltage problems, margin computations had been done for all the busbar faults of the area with a consumption increase on the East area. Simulations were made with snapshots from the beginning of February. The simulations showed only local voltage important decrease with one busbar fault in the East area in a particular condition. It happened when a node was exploited with only one busbar, thus the loss of this busbar induced a local system collapse. Indeed this disturbance led to the loss of two close units due to the protection against under-voltage of the units. After these losses, a transmission line was overloaded and disconnected after 60 seconds. When this line was disconnected, the model diverged. Figure 4.8 shows the voltage evolution on several nodes for this disturbance.

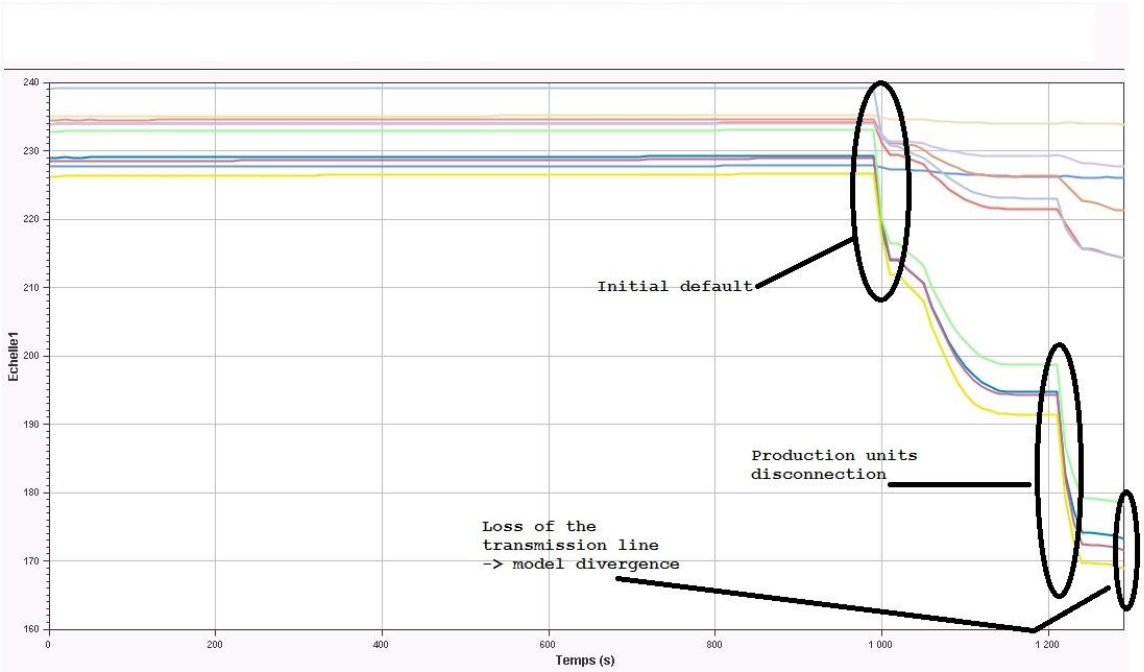


Figure 4.8 *Local system collapse*

However, this particular node is only exploited with one busbar in some rare cases. For example, it had been exploited with one busbar only during fifteen days last year. For all the other simulations and variations done (unavailability of generating units for example), no local problem was detected. As a result, it was decided to give up the static criterion of the East area.

4.1.2.3 IMPROVEMENT OF ASTRE DATABASE AND DYNAMIC SIMULATIONS ON THE EAST AREA

The switch to dynamic simulations implied a completion of the database of Astre by adding the Swiss production units. That was done in a similar way as for the German and Belgium generating units. The impact of the database can be illustrated by comparing the voltages on some nodes situated close to the borders for a disturbance with the old and the new databases. Voltage values after the disturbance are provided in Table 4.2 and Figure 4.9 illustrates the differences between the two databases:

Database	U (Node 1)	U (Node 2)	U (Node 3)	U (Node 4)	U (Node 5)
Old	364 kV	391 kV	410 kV	205 kV	222 kV
New	357 kV	388 kV	408 kV	199 kV	219 kV

Table 4.2 *Voltage values for the old and the new databases*

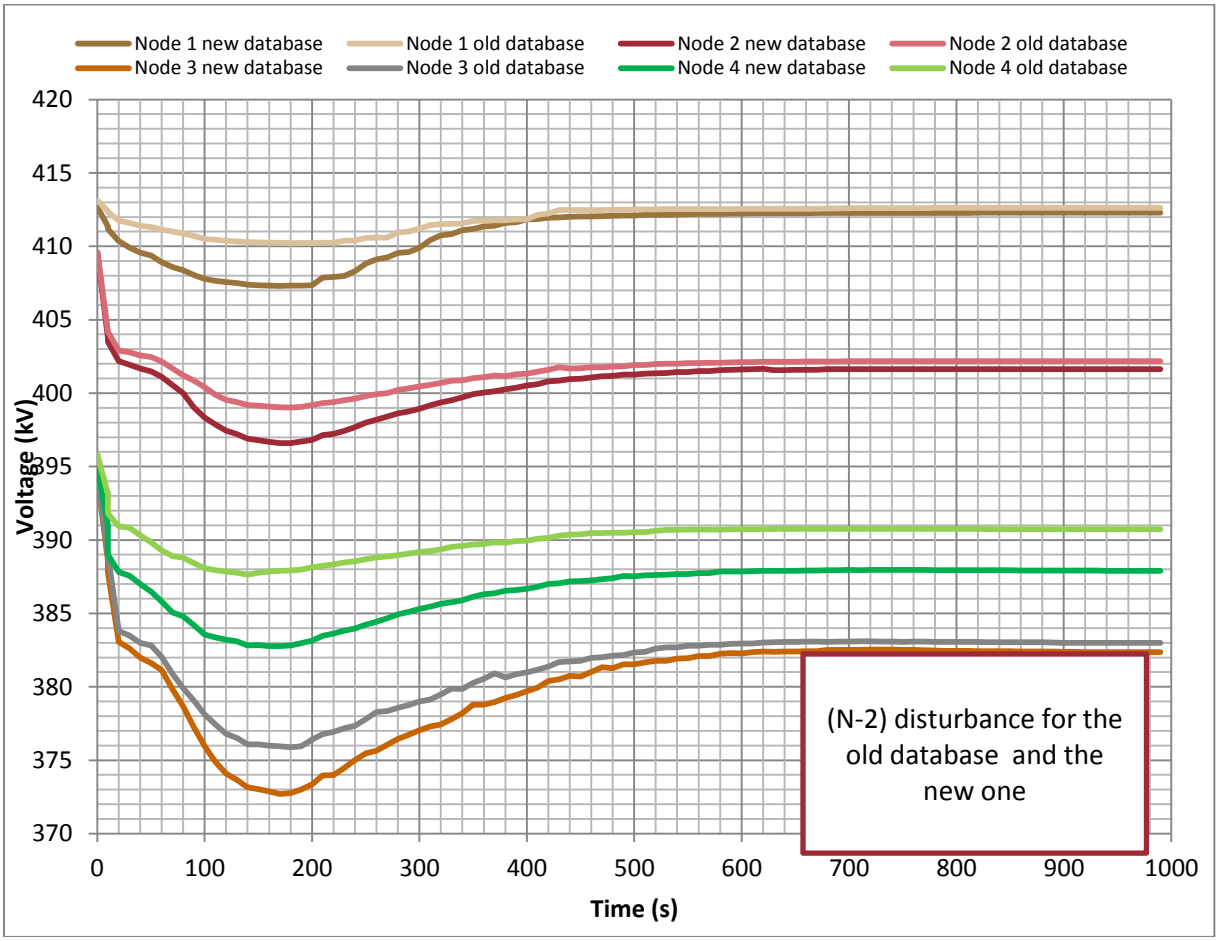


Figure 4.9 *Voltage evolutions for a (N-2) disturbance for the old and new databases*

The different simulations also showed that there was no voltage problem at all on the East area even during the most stressed system states from last winter, at least for busbar and

line fault, except the particular local system collapse presented in the previous section. Even for consumption increases on Paris-Normandie and East area on the same time, there was no voltage problem detected with busbar faults and (N-1) line fault. As a consequence, there will only be on-line dynamic simulations on the East area when there is a topological modification on the eastern part of the East or unusual conditions on the network.

4.1.2.4 CONCLUSION

The work showed that the static criterion was no longer suitable for the East area. There is only one zone at the eastern part of East area where there can be local system collapse in particular conditions (exploitation at one bus of some nodes for example). After the improvement of the Astre database, the simulations have shown that, except from the system states described in the previous sentence, there are no voltage problems due to (N-1) busbar faults on the East area, whatever the area on which the consumption increase is done, and as a consequence the static criterion is suppressed and on-line dynamic simulations will be done with busbar or line faults on the East area only when there are unusual conditions or topologies on the eastern part of the East area.

4.2 LSD SIMULATIONS

This section will deal with the simulations done in order to find a new activation level for the LSD global mode. After introducing the reasons that have motivated the study and the work hypothesis, I will present the results obtained and the conclusions of the work.

4.2.1 NECESSITY OF THE STUDY AND WORK HYPOTHESIS

The LSD had been presented in 2.3.2.2 and its operating modes had been explained. As you may know now, the LSD global mode is a severe countermeasure against system collapse because its action will lead to the load-shedding of around 3 000 MW. As a consequence, it is important to activate it only in case of necessity. Exceeding a given consumption level led to the activation of the global mode. Until last winter, this consumption level hadn't be approached but the peak consumption from last winter was quite close to this level so it was decided to check its validity. This level had been calculated in the design studies done before the installation of the LSD three years ago and many investments have been done since in the area in order to improve the voltage stability (capacitors particularly). Thus it seemed natural to make new studies to determine a new activation level.

The study had been done on the most stressed system condition with the biggest consumption level with Eurostag software. After a conversion of the snapshot into files exploitable in Eurostag software, we prepared the study by making modifications on the files and by making work hypothesis. First, we only simulated the HV network on the area under study and a neighboring area whose evolution is linked to the evolution of the area where the LSD is installed. On the other parts of the system, only the EHV network was taken into account. Then on the two areas quoted previously, the load had been simulated under two load-tap changer levels (a EHV-HV LTC and a HV-MV LTC), that is on the distribution level. Undervoltage protection scheme was added in the dynamic file for all the groups of the two areas. This protection disconnects the production units if the voltage at their connecting point becomes lower than 0.8 U_n.The system collapse that we want to escape from is a system collapse due to cascading losses of production units due to undervoltage protection scheme after an initial (N-2) fault. The line overloads had not been taken into account, this means that if a line is overloaded during the simulation, it isn't opened. This approximation had been done because we focused on a fast system collapse with a time-scale of 10 to 20 seconds before the minimum time constant of line disconnection due to overloading (60 s). After the Eurostag studies, the consumption increases were simulated in Convergence software and we checked that they didn't induce 1 minute overloads .We were only interested in 1' overloads because we considered that the operators can face longer overloads and take topologies measures to avoid the line disconnection. We didn't observe any 1' surcharge.
The simulations on Eurostag software had been done in two phases:

- First a consumption increase with LTCs action simulated
- Then the (N-2) disturbance without LTCs action (there is no tap change in the first 30 s after the disturbance and we were interested in system collapse in the first 10 to 20 seconds)

Something must be added regarding the consumption increase and the actions of LTCs. 2.3.2.3 stated that there are voltage values controls in order to block the LTCs. During the

consumption increase simulated in this first step, some of the thresholds were reached but the LTCs were not blocked in order to have a real consumption increase equal to the consumption increase order. Indeed, if the LTCs are blocked during the consumption stress, the real consumption increase will not be equal to the consumption increase order (due to the voltage dependence of the load). LSD normal mode had also been included and adapted. It is an Eurostag dynamic file with the name of the loads that must be shedded. The loads names vary from one snapshot to another (because the number of busbar of a node can vary from one snapshot to another) and so modifications were necessary. The last thing worth mentioning is that cases with one or two generating units unavailable in the production center where the (N-2) disturbance is done had been also simulated.

4.2.2 RESULTS

4.2.2.1 WITHOUT GENERATOR UNAVAILABILITY

The first case studied corresponded to the original snapshot without generator unavailability so with the complete network of the snapshot.
A consumption increase of 1900 MW had been simulated to reach a very high consumption level. The (N-2) disturbance at this level didn't lead to a fast system collapse; the voltages after the disturbance were still higher than the voltage level for unit disconnections due to undervoltage protection scheme. The voltage decrease was around 15 kV at the connecting points of the generating units. Figure 4.10 displays the voltage evolution at the connecting nodes for the generating units of the area.

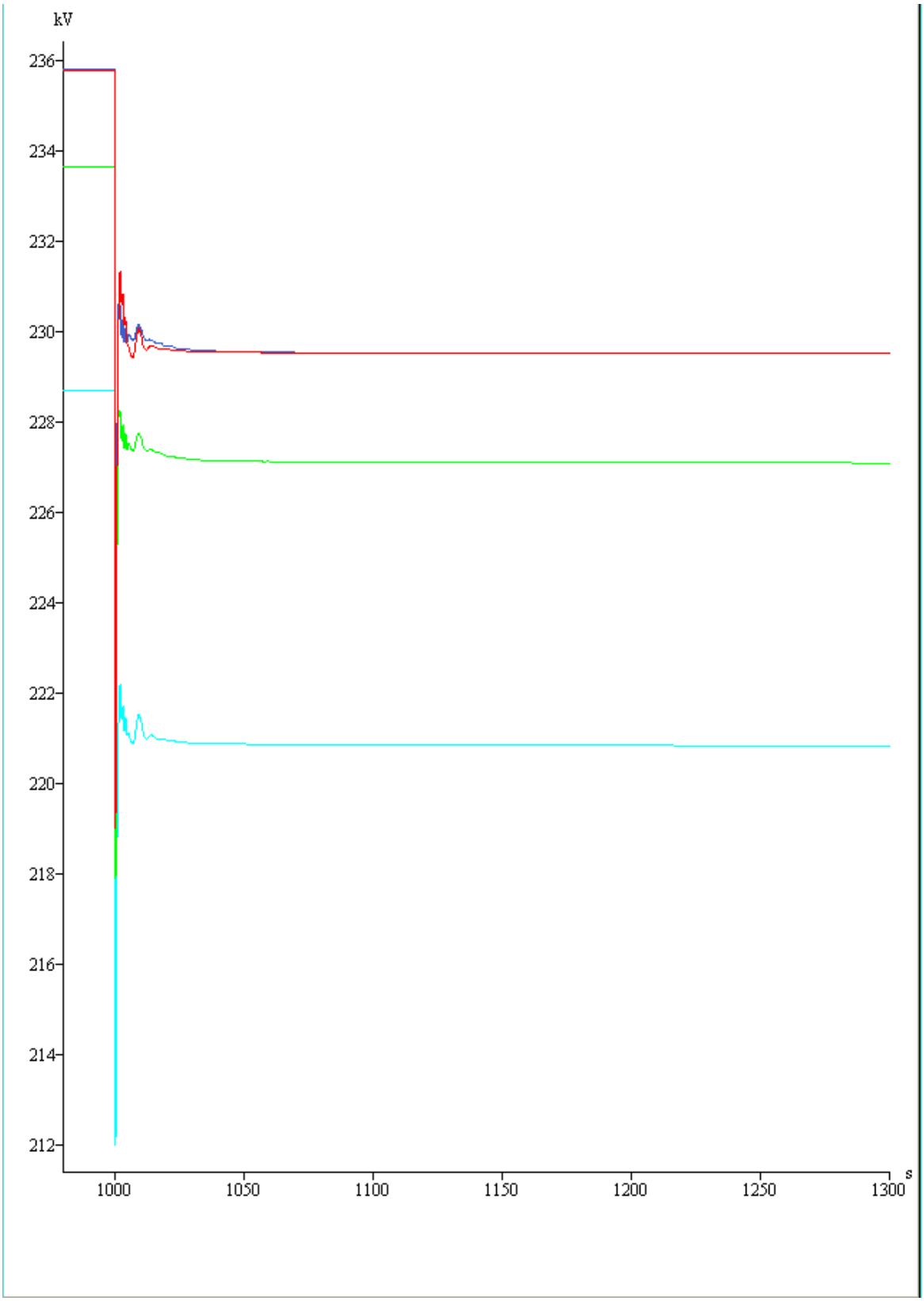


Figure 4.10 *Voltage values at the connecting points for area's generating units (connected at the 225 kV network)*

4.2.2.2 WITH ONE GENERATING UNIT UNAVAILABLE

In these simulations, one generating unit of the coal production center had been disconnected from the network.

In this case, it was not possible to simulate a consumption increase of 1 900 MW because this consumption increase led to the disconnection of several close units due to the action of undervoltage protection scheme and so to voltage decrease. As a consequence, we had made a first consumption increase of 1 650 MW with LTCs actions and then a "second consumption increase" of 250 MW of consumption increase order (the voltage was no longer kept at its set value for the loads) in order to get a total consumption increase order of 1 900 MW.
The (N-2) disturbance didn't lead to system collapse but the voltage values after the disturbance were closer to the values implying the disconnection of the units due to undervoltage protection scheme. The voltage decrease after the disturbance was around 30 kVFigure 4.11 shows the voltage evolutions after the disturbance.

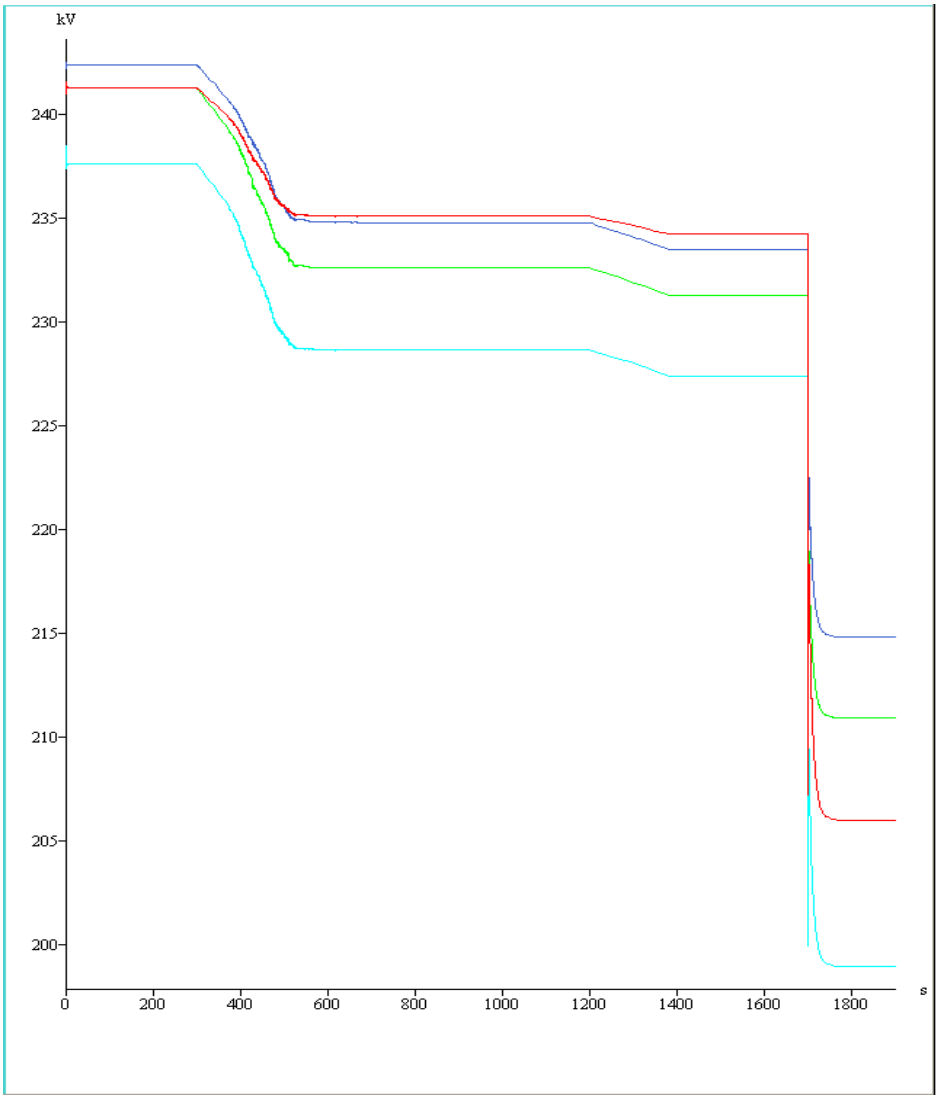


Figure 4.11 *Voltage values at the connecting points for some generating units with one generator unavailable*

4.2.2.3 WITH TWO GENERATING UNITS UNAVAILABLE

In this case, two generating units of the production center were unavailable and disconnected from the network.

It was not possible to make a consumption stress of 1 900 MW without blocking the LTCs because there was a divergence similar to the one explained in the previous section.
The maximum consumption stress that it was possible to simulate with the LTCs action was 1 500 MW. After this first consumption increase, the LTCs were blocked and a second consumption increase of 400 MW was added (the voltage at the loads nodes was no longer kept at its set value).

The (N-2) disturbance at this consumption level led to a fast system collapse due to the actions of the protections against under-voltage. The last consumption stress that didn't lead to a fast system collapse is a stress of 1 650 MW. The losses of the two units at this level induced a system collapse in 17 s without the action of the normal mode of the LSD. However, when this action was simulated, the system collapse was avoided thanks to the shedding of one level of load on three subzones (see Figure 4.12). A stress consumption of 1 700 MW induced a fast system collapse even with the action of the LSD normal mode but the LSD global mode is sufficient to pass the situation(see Figure 4.13).

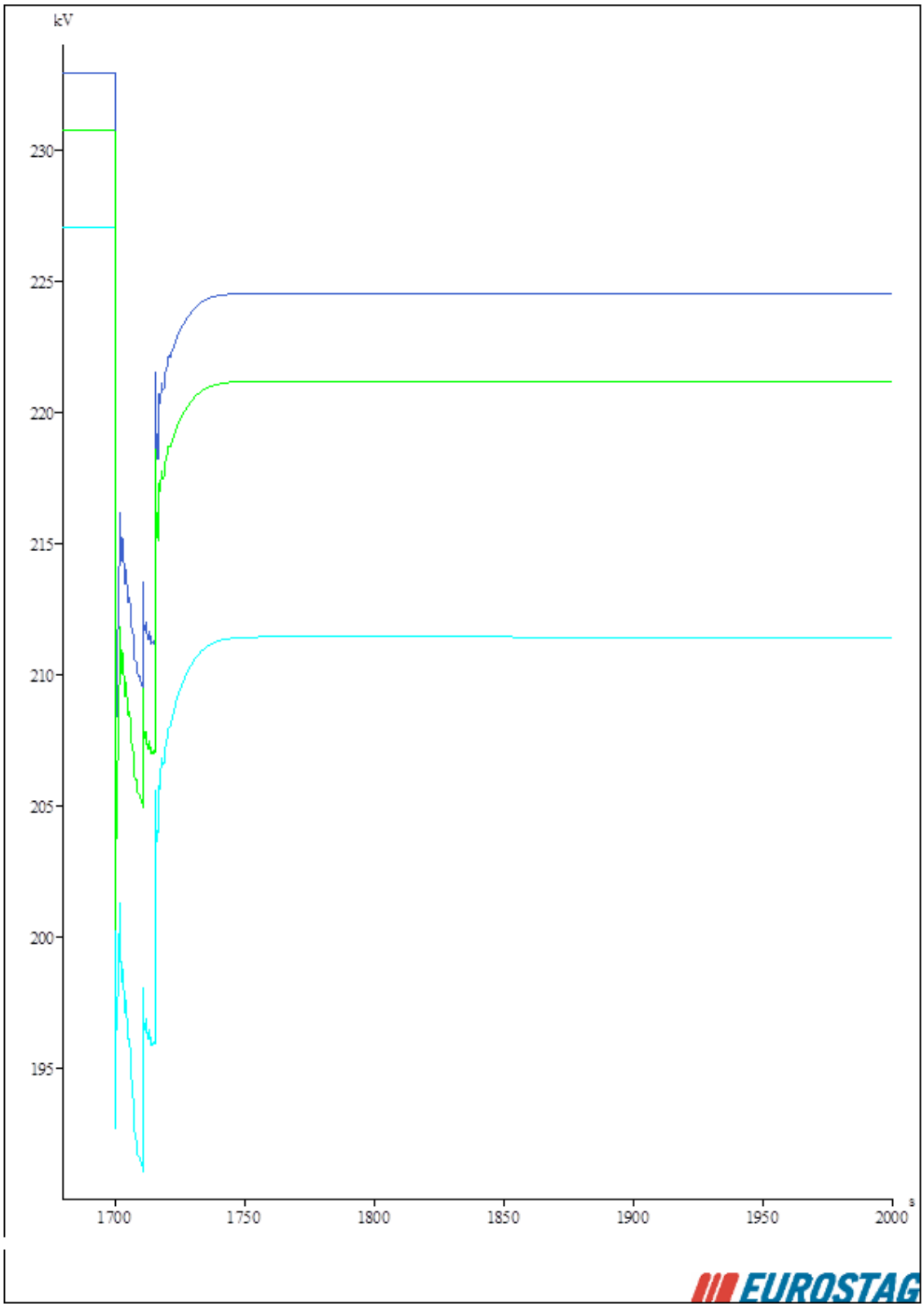


Figure 4.12 *Voltages evolution for a 1650 MW consumption increase with ADO normal mode operating*

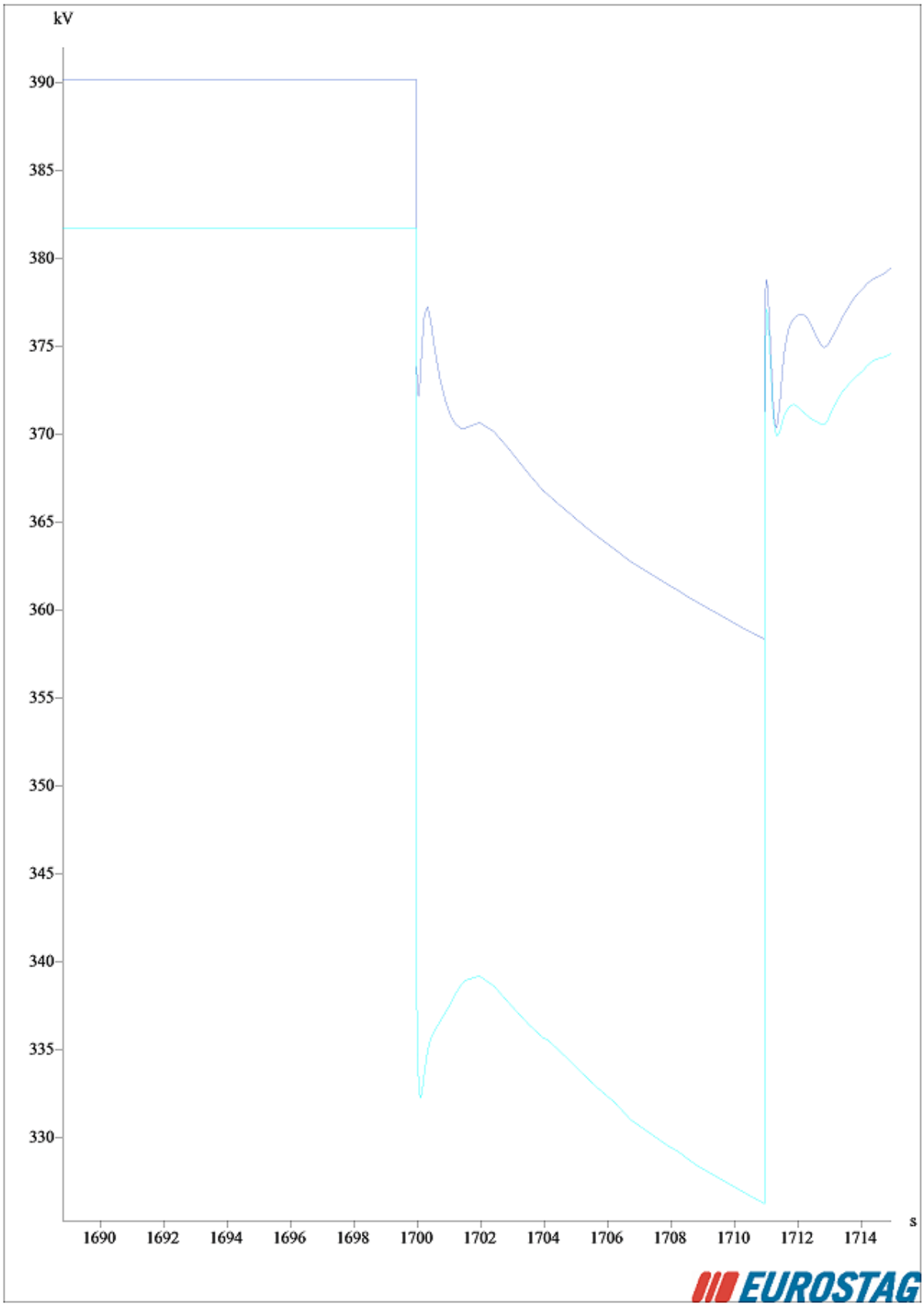


Figure 4.13 *Voltages evolution with action of LSD global mode for a 1 700 MW consumption increase*

4.2.2.4 WIND POWER PLANTS RESPONSE

In order to take into account the uncertainties about the response of the wind power plants during the transient phase following the disturbance (risk of disconnection of the units), complementary simulations were done. The hypothesis chosen to consider this uncertainty had been to add a consumption step simultaneously with the (N-2) disturbance. As can be seen on the Figure 1.6, for the 8th of February, the participation factor was of 30% for the North part of France so as the wind potential on the area under study is equal to 2 000 MW, we simulated a consumption increase in step of 600 MW at the same time than the disturbance. The maximum consumption increase before system collapse with this additional constraint was 1 350 MW with two generating units unavailable. Without unavailability of generating unit, a consumption increase of 1 900 MW didn't lead to system collapse.

4.2.2.5 CONCLUSION

Based on the simulations results and keeping a security margin because the simulations had been done only on one snapshot (because it is a time-consuming task to adapt the files) and to take into account the defaults of the model, the consumption level for the activation of the LSD had been increased by 800 MW for a complete network and 600 MW in case of unavailability of a generating unit. The new thresholds are respectively 1200 MW higher than the consumption of the 8th of February with generating unit unavailability and 1400 MW without unavailability of generating unit. This study had been presented in RTE. As a result, these thresholds will be applied for next winter.

4.3 OTHER TESTS AND SIMULATIONS

Other tests and simulations made during the Master's thesis work will be presented. The common point of these studies is that they are all related to voltage stability and to the improvement of voltage security in the French network. They have been done in parallel with the main topics of the Master's thesis and are the results of interrogations and reflections that some results obtained and observations done have risen. Even if they were not in the Master's thesis original projects and proposal, it is interesting to present these trials which enter in the global work and context of the thesis: reflections about voltage stability.

4.3.1 TESTS ON LOAD-TAP CHANGERS

The following observation had been done in the French network. In the majority of the system collapse observed, what is really preponderant is the LTCs action which amplifies in degraded conditions the system collapse. It is really rare that a disturbance directly induces other losses (transmission lines losses due to overloading or units losses due to undervoltage protection scheme) before LTCs action. LSD simulations were the perfect anti-example because it focused on system collapse due to cascading generating unit disconnections but it remains a rare phenomenon. Our idea was to change the time constants of the LTCs action by increasing the time distance between the tap changes and by blocking the LTCs sooner. In RTE models, the first tap change is done 30 s after that the voltage value exits the acceptable voltage range for the node whose the voltage is controlled for transport LTCs and 60 s for distribution LTCs and two tap changes are separated by ten seconds. The last time constant was changed in Astre database in order to measure its impact (increase of the time between two tap changes to 20 s, 30 s and so

on until 60 s). As described in 2.3.2.3, the LTCs can be blocked in a zone when the voltage becomes lower than a minimal voltage value at the pilot point of the zone. But there is a time constant during which the voltage must be under the minimum value before the blocking of the LTCs. It is currently 30 s and we decreased this value to 10 s and made simulations on the stressed system states from last winter. We also tried with the combination of the two changes quoted previously. Table 4.3 shows some results obtained:

System state	*Contingency*	*Max. Cons. Increase*
08/02	Worst contingency	200 MW
08/02 with changes[8]	Worst contingency	219 MW
03/02	Worst contingency	1031 MW
03/02 with changes	Worst contingency	1094 MW

Table 4.3 *Results obtained with LTCs time-constant changes*

We weren't entirely satisfied with the results because for the most stressed system state, there was no increase of the maximum acceptable consumption increase. The only gain was a gain of time: the system was collapsing more slowly. In most cases, the gains are quite limited compared to the importance of LTCs in the system collapse. These results were surprising and as a consequence, we tried to block all the LTCs zones. However, some LTCs are not blocked because they represent industrial installations connected directly to the network. Nevertheless, it would be good to have a good understanding of their behavior and to know if they are all still in operation. An enquiry has begun in RTE to get more information on these LTCs and better represent them. Once the results of this enquiry are known, it could be worth redoing this study on LTCs.

4.3.2 STUDY ON (N-2) LINES

The last experiment done in the Master's thesis has been an experiment on (N-2) double lines disturbance. Double lines are two lines which are on the same pylon: the loss of these units can be considered as a (N-2) lines or a (N-1) pylon (RTE uses more the denomination (N-2) double lines fault). Indeed, during the tests done in order to suppress the static criteria and to validate the new database, we observed that several (N-2) double lines disturbance led to global system collapse still on the same zone (Parisian area and South of North area) for consumption levels inferior than the lowest undesirable consumption level for (N-1) generator disturbance. In other words, there existed consumption levels at which these (N-2) double lines disturbance led to system collapse whereas (N-1) generator was stable. In operational context, during voltage crisis, these faults are not always covered.

In any case, the goal of my study was to make a list of these (N-2) double lines disturbances that were more critical than the worst (N-1) generator. In order to do that, margin calculations were made on Convergence software. The results spotlighted that there were system collapses for double lines supplying Paris area disturbance. Indeed, there were two or three (N-2) disturbances on each of the areas surrounding Paris (West area, North-East area and East area) which led to a system collapse for a lower consumption stress than the worst (N-1) generator. The explanations are not exactly the same for all these system collapses but the

[8] Changes are the increase of the time between two tap changes to 60 s and the decrease to 10 s for the LTCs blocking scheme time constant.

similarity is that the disconnected lines are very highly loaded and supply the Parisian area. The losses of these lines induce a power redistribution which consequently lead to system collapse.

Since the system collapse still happened on the same geographical zone, we decided to discuss the pertinency of the installation of an automatic load-shedding device in the problematic area. In order to make the simulations, we used the existing structure of LSD and modified the nodes on which the load-shedding is done as well as the nodes for which the voltage value is controlled. The first part of the study was to determine which nodes could be used as detecting nodes (detecting node is the node on which low voltage value will trigger the load-shedding mechanism). We simulate on Eurostag for the 8th of February the different (N-2) double lines disturbances and plotted the voltage responses in unstable cases. In order to have a detecting node efficient for all the cases, it should have quite the same voltage evolution for all the problematic disturbances to trigger the load-shedding mechanism soon enough. Indeed, if the detecting node is not sensitive to one of the disturbances, there will not be any load-shedding after this particular disturbance and the system can collapse. Moreover, the system was collapsing after the action of the LTCs and disconnections of some units from the network due to the undervoltage protection scheme. As soon as a crucial unit is disconnected in a degraded system state the system can go to collapse. Therefore, it is necessary that the activation of load-shedding occurs before the disconnection of any unit but not at a too high voltage in order to avoid untimely and unnecessary shedding. By observing the results of the simulation, it was possible to find two detecting nodes with an acceptable detection level that can't be given for confidentiality reasons.
Then we have determined how much of the load must be shedded. In France, the loads are assembled into zones inside the areas and so when TSO has to shed load, it uses these zones. Test had enabled us to determine the quantity of necessary load-shedding to pass all the (N-2) double lines disturbances. Figure 4.14 displays the case where the amount of load shedding is sufficient to prevent system collapse whereas Figure 4.15 shows the case where the amount of load-shedding is too reduced.

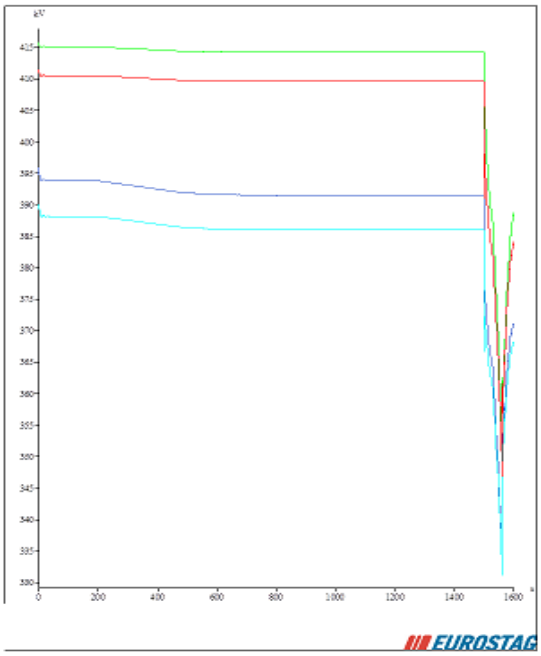


Figure 4.14 *Sufficient load-shedding*

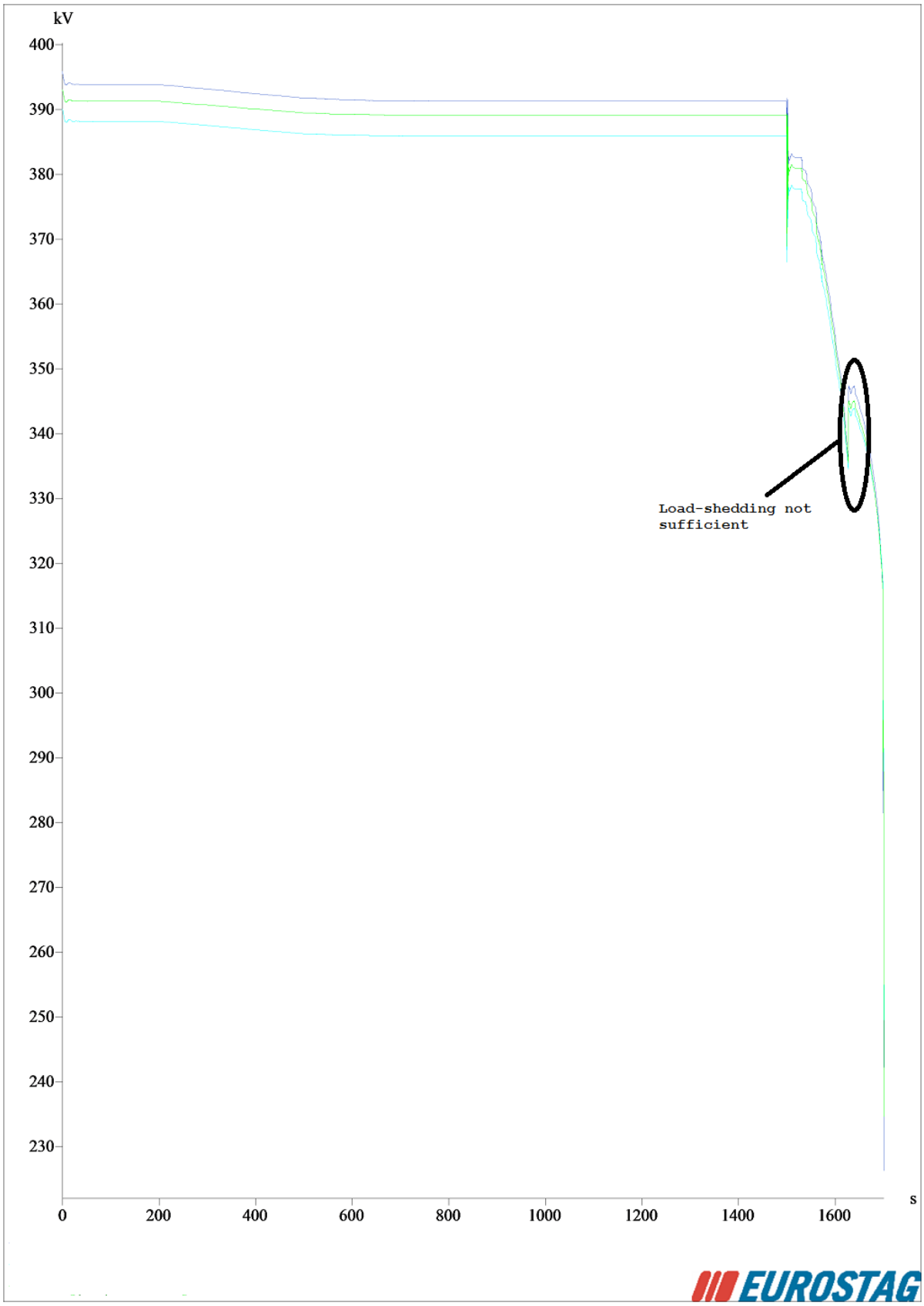


Figure 4.15 *Insufficient load-shedding*

These simulations showed that the installation of another automatic load-shedding device on the French network could be considered and will improve the network security during voltage crisis. It could protect the system against (N-2) double lines disturbance or even (N-2) generators if we accept to shed an important amount of load. Discussions will be led in the future in RTE about the results of this study and the conditional pursuit of studies on this topic. The study presented was only a first approach of the problem.

5 CLOSURE

5.1 CONCLUSION

Due to the context evolution of the energy sectors (consumption increase, development of renewable energies, etc.) leading to challenges for TSOs, power system security becomes complicated to ensure. Voltage security, which is a part of power system security, must be guarantee in any conditions. This leads TSOs to make studies at different time span, such as week-ahead or day-ahead, in order to check that the system will stay in an acceptable state satisfying the (N-1) criterion. One of the important tools for voltage security assessment for the French network is the use of static criteria assessment. These criteria are checked for a contingency list from week-ahead simulations to daily simulations. They must be efficient (they don't detect acceptable state as undesirable), simple (easy to use) and conservative (they have to detect all the undesirable system states as undesirable in order to not jeopardize the system security). As a consequence, they must be updated from time to time to remain adapted to the network and its evolution. In order to update these static criteria on the North-East and the East areas of the French network, RTE initiated this thesis. In addition to the tools used to ensure voltage security assessment and satisfy (N-1) criterion, protection and defense devices are also designed and built in order to prevent the system from collapsing after disturbances such as the simultaneous loss of two generating units or two EHV transmission lines. One of these tools for the French network is a load-shedding device which is installed in one area subject to voltage stability problems. This load-shedding device was installed three years ago and has in particular a global protection mode that can shed load up to 3 000 MW. This global mode has been designed to avoid system collapse when there is a particularly serious disturbance which is the loss of two generating units of the area's main production center. It is only activated when the consumption level is higher than a predefined value. However, investments have been done in the area under study and so the activation level is no longer adapted so a study was necessary for the determination of a new activation level.

The search for new static criteria on the North-East area has been done following the classical methodology. The first step was the definition of a contingency list (with all the busbar faults), the choice of system states and stopping criteria for dynamic simulations. Margin computations and load-flow simulations were then run. However the first set of results showed clearly that the criteria used were no longer conservative and that it would be difficult to build new efficient and simple criteria. These observations and the fact that the faults led to global system collapse orientated us to the decision to give up static criteria on this area and to conduct experiments to switch to on-line dynamic simulations. Three points should be done before this change could be validated:

- An improvement of Astre database to take into account the reactive power production limits of the foreign groups
- A check of the decision validity: the confirmation that no local system collapse was possible
- An addition of the most limiting disturbances for dynamic simulations

Dynamic simulations allowed concluding to a definitive withdrawal of static criteria on the North-East area. For the East area, the approach has been lightly different due to the results obtained with the North-East area. Indeed, we first searched for local voltage issue but the simulations showed that, in normal conditions, there was no problem so the static criterion was deleted. Astre database has been improved with the addition of data for the Swiss generating units. Dynamic simulations run showed that there was no disturbance from the East area leading to global system collapse for normal consumption levels (maximum consumption increase = 2 000 MW) with consumption stress either on East area or Paris and Western areas.

Eurostag simulations have been done for a day of this winter with the complete network as well as with unavailability of one or two generating units to find the new activation level for the load-shedding global protection mode. This level was increased after the analysis of the results and will be used for next winter.

This Master's thesis work was included in a more global work led each year from spring to winter by RTE engineers. This work aims at analyzing the situations lived during the winter where low voltage problems are crucial and at reinforcing the network security to avoid system collapse. The results are used to prepare the next winter and to improve RTE knowledge and understanding of its network.
One interesting fact in this thesis is the upheaval in goal due to the results obtained. From an initial objective of updating static criteria if necessary, the Master's thesis finally ends up with the withdrawal of the static criteria and to the passage to dynamic simulations for the two areas under study. This thesis work analytically presents that dynamic simulations are more adapted to ensure that the stability of power systems, especially interconnected areas, is ensured. It also spotlights the necessity of on-line dynamic simulations instead of static simulations.

5.2 FURTHER WORK

Further studies can still be led in order to improve the voltage security on the French network. There is still an area using static criteria – Rhône Alpes Auvergne area – and the same kind of study that the ones presented in this report for North-East and East areas can be conducted to see the pertinence of these criteria. Moreover, power transfers between countries and neighboring countries networks modeling are important factors for system security. Studies led in cooperation between different TSOs must be increased to improve networks voltage security. Using a better model for the foreign networks in on-line studies thanks to the insertion and the use of DACF files could therefore be seen as a way to improve the system security. Another point that is interesting for further developments is the analysis of the mechanisms playing a role in the system collapses and the system collapse evolutions to design and have an efficient response to these collapses. Indeed, the grid changes (investments for example) and the society evolutions (consumption increase, development of electric vehicle for instance) lead to changes in the voltage stability field with less differentiation between load and generating centers for example. It is thus crucial to always control the behavior of the components playing a role in the voltage stability issues and understand these problems in order to ensure and improve system security.

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