Capacity allocation using the flow-based method

Master of Science thesis by
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KTH Electrical Engineering
Electrical Power System
Since 2000 the European electricity market has been opened and has had for main purpose the consolidation of the competition thanks to the increase of the numbers of actors. Today the electricity market catches up more to a juxtaposition of regional or national markets than to a real integrated market. Indeed cross-border congestions run counter to the elaboration of a competitive market. In that context the optimal utilization of the available capacities is a major issue. Some progresses have already been realized concerning the allocation, with the setting up of explicit auctions and market coupling. The economical gain will now come from a best evaluation of the available margins for the cross-border exchanges. This improvement could be realized thanks to the flow-based method.

This master thesis is part of a Research and Development project which aims first of all at validating the efficiency and robustness of the flow-based method and also at setting up the tools and procedures for an operational use of this method.

The present master thesis report explains the interest of the flow-based method compared with the method based on Available Transfer Capacity before explaining the principle of the Flow-based method. Finally the report exposes different tests to analyze the flow-based method. The results obtained show that the adoption of flow-based method will be a real improvement but will require a total coordination of all the actors concerned.

This report aims to be useful for people who have to work on a project related to the cross-border exchanges. The other aim of this report is to be understandable by the lay person. Thus it will be useful for anybody who is interested in cross-border electricity exchanges even if it is not his domain of study.

Keywords: power system, electricity market, cross-border exchanges, flow-based.
First of all I would like to thank Jean-Yves Bourmaud, my supervisor at RTE, and Emanuele Colombo for offering me the possibility to work on a very interesting subject that has enabled me to use my academic knowledge and also to learn a lot on a very challenging topic.

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### Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Signification</th>
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</thead>
<tbody>
<tr>
<td>EDF</td>
<td>Electricité de France (Major company of electricity production and distribution in France)</td>
</tr>
<tr>
<td>RTE</td>
<td>Réseau de Transport Electrique (the French TSO and owner of the national transport network)</td>
</tr>
<tr>
<td>VHV</td>
<td>Very High Voltage</td>
</tr>
<tr>
<td>ISO</td>
<td>Independent System Operator</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission System Operator</td>
</tr>
<tr>
<td>ETSO</td>
<td>Association of European Transmission System Operators</td>
</tr>
<tr>
<td>UCTE</td>
<td>Union for the Coordination of Transmission of Electricity</td>
</tr>
<tr>
<td>DACF</td>
<td>Day Ahead Congestion Forecasted</td>
</tr>
<tr>
<td>NTC</td>
<td>Net Transfer Capacity</td>
</tr>
<tr>
<td>ATC</td>
<td>Available Transfer Capacity</td>
</tr>
<tr>
<td>GSK</td>
<td>Generation Shift Keys</td>
</tr>
<tr>
<td>PTDF</td>
<td>Power Transfer Distribution Factor</td>
</tr>
</tbody>
</table>

- **Power system**: Set of means of electricity production, transport and distribution (national electricity network)

- **Marginal price**: Price of the last selected bid in the merit order.

- **Spot price**: Price set by the intersection of the selling and the buying bids on the spot market.

- **Explicit auction**: Auction where the product sold is a right to program an exchange on a given contractual path.

- **Implicit auction**: Auction for which the allocations capacities are combined with the functioning of an organized electricity market.

- **Market coupling**: Consists in a coupling of N markets, according to a decentralized approach, resulting in a unique virtual market as long as the interconnections capacities are not saturated.

- **Market splitting**: One market which is split in N independent virtual markets when the capacities are saturated.

- **Market value**: The linear combination between the bid price and the allocated capacity
• **Option**: If the capacity is allocated in the form of option, the actor gets a right to program an exchange and can then carry out its right during the nomination. Thus the volume of the transaction could be lower than the volume of the right. An option is the reference solution in Europe [1].

• **Obligation**: If the capacity is allocated in the form of obligation, the actor has to carry out the right from the purchase. Thus the volume of the transaction is equal to the volume of the right. Obligations are only used in Scandinavia [1].

• **NTC**: The net transfer capacity represents the best estimate limit for physical electricity transfer between two areas.

• **ATC**: The available capacity which can be defined for different periods of time (year, month, day…)

• **Critical branch**: A line of the network which could probably limit the commercial exchanges between the areas because it often reaches its physical limits.

• **Participating nodes**: These nodes represent the junction point of the units to the network where the production varies significantly when the total production of the zone varies.

• **PTDF**: Based on a state of the initial network, this is the influence on the flow on a critical branch of every additional MW injected at a participating node.

• **GSK**: Quantity which represented the ratio between the variation of production at a node and the global variation of production of the corresponding zone. It is approximately equivalent to the forecasted merit-order of a price zone.

• **Physical margin**: It measures the acceptable flow variation in a branch. It is equal to the difference between the maximal flow and the reference flow.

• **Netting**: Take into account that the exchanges in an opposite direction counterbalance each other.

• **Approximation of the direct current**: approximation where the following hypotheses are taken into account:
  - \( V_i = V_N \) where \( V_N \) is the corresponding nominal voltage
  - \( R=0 \)
  - No losses
  - The angles \( \theta \) are small and thus \( \sin(\theta) \approx \theta \)
1.1. **Background**

The power grids have been built for transporting at any time the generated power to the consumers, with the best cost and by assuring the security of goods and individuals.

Since February 1999 the European electricity market has been opened and as a consequence the activities of generation and supply have been parted from the activities of transmission. The latter are now realized by the transmission grid operators which have to guarantee the free, fair and non-discriminatory access to the VHV grid for generating companies and consumers.

The building of a real integrated European market rather than a simple juxtaposition of national markets must enable to consolidate the concurrency by increasing the number of participants.

1.2. **About RTE**

- **Mission**

The initials “RTE” refer to the unique operator of the French high voltage and extra high voltage public power transmission system.

The power transmission network in France includes all of the high and extra high voltage power lines and transforming substations which connect the power plants, distribution networks, industrial sites and the power networks of neighboring countries.

As explained in [2], the existence of RTE made official on the 1st July 2000, results from the Act of February the 10th 2000 concerning the modernization and development of the electricity public service. This Act calls for the opening of the French electricity market and stipulates that the Transmission System Operator must be independent from the other activities of EDF.

RTE’s role is to ensure the continuity and quality of the public power transmission service. RTE carries out an essential public service mission: providing equitable access for all the users of the power transmission network (63, 90, 225 and 400 kV).

To fulfill its various tasks, RTE must ensure:

- The balancing of generation and consumption at all times
- The operating safety of the power system
- The maintenance and development of the public power transmission network.

- **Organization**

As written in [2], RTE comprises four divisions and has 8000 staff members who are divided up between the Operational Units and the Central Functions, as illustrated in the Figure 1-1:
RTE’s activity is organized around two major inseparable fields:

- The power system and flow management
  - Network access
  - Power system safety
  - Efficient management of network development

- Power transmission and network management
  - Network maintenance
  - Network development engineering

**Power Network – How does it work?**

Thanks to the liberalization of the electricity market, an eligible European consumer is able to buy electricity everywhere in Europe.

Electricity is conveyed via RTE’s facilities, high and extra high voltage lines and transforming substations. RTE therefore has to direct the power through its facilities and ensure the balance between the electricity demand of consumers and the supply of power generating companies.

The necessary co-ordination of energy flows requires the effective know-how of the national control centre and the seven regional control centers. The load dispatcher’s work with computerized diagrams of the areas which they have to monitor; thus, they can keep an up-dated view on all the facilities and their state of operation.

In this way, they are able to act almost immediately in the event of contingencies or outages so as to adapt the network configuration and allow power to be conveyed at all times.
1.3. **Aim of the project**

The master thesis is actually a part of a greater project. The aim of this big project is to be sure of the feasibility of the flow-based method. Indeed today the flow-based method is a theoretical construction, and that is why the robustness and the relevance of the method have not been tested on real data yet. In this perspective the two principal aims of the global project are:

- to produce flow-based parameter thanks to realized data of a European network and to analyze the robustness of the results.
- to elaborate a methodology and try to realize experimentation in real condition

1.4. **Thesis work outline**

The thesis work focuses on the first part of the project presented above, which means to compute some tests on realized data in order to determine the relevance of the method.

Before starting any kind of tests the first step is to have a good understanding of the context and of the method. Indeed it is very important to have a good understanding of what the different quantities introduce in the flow-based method represent. Then it is important to do isolated tests before starting a set of tests on successive dates. This first testing part will enable us to calibrate our tools. Indeed another important point of this project is that all the tools used during the project are experimental tools, and for the major part they need to be tested before utilization. Thus an important part of the internship has also been to elaborate some simple computer programs or to test some computer programs elaborated for the treatment of data. And finally after the first test the general test on successive data could start.

1.5. **Outline of the report**

The thesis report will try to explain as clearly as possible the flow-based method and to present the tests and their result. It will be divided in several chapters:

- First a general chapter, to provide the reader who is not acquainted with power system and electricity market with the important keys in order to understand the following. The other interest of this part is to briefly present the limitations of the current method of capacity allocation.

- In a second chapter the flow-based method will be presented. To facilitate the understanding of this theoretical approach an example will illustrate each step of the flow-based method.

- Finally in the third and fourth parts, the implementation of the tests and the results will be described.

- The appendices contain some complementary information which can help the reader to have a better understanding, like the fifth appendix which gives additional information concerning the marginal prices. They also present complementary works like the validation of computer programs for instance.
Chapter 2.
From grid to market: general context

2.1. From power system ...

2.1.1. The structure of the electric power system

As written in [3], the term power system refers to all kind of system which includes one or more generators, which supply one or more loads via an electric grid. Here the presentation will focus on large power system which means system supplying a large number of consumers. This kind of power system is organized with a hierarchical structure as illustrated in the figure 2-1: The grid has for goal to transfer energy from the generation part to the consumption part.

![Figure 2-1: Structure of Power system](image)

- **Transmission grid**
  
  At the high level we find the transmission grid. It is at this level that the project is situated. Indeed this study focuses on the cross-border exchanges and for a country it is often this part of the grid which is directly connected to the neighboring transmission grid. The transmission network connects the main power sources and transmits a large amount of electric energy. To
achieve its task of energy transmission, the transmission system needs a high degree of efficiency. For instance it must be able to optimize the generation of its own country and also support the trading with the neighboring country. At this level the security of the network is a very important point, it is necessary to be able to withstand a change of topology of the network like for instance the disconnection of one or several lines after an outage or a storm. It is important to keep in mind that the network is meshed and although each country is responsible of its part of the grid, an incident in a country will have consequences for all its neighbors. A good illustration of this interdependence of the grids is the incident of the 4th of November 2006 where the disconnection of one line in Germany had consequences on a big part of Europe.

D Brief description of a grid

Different elements are necessary to describe schematically a grid. A network is first a set of lines which could be single or multiple. All the locations where a line ends are called nodes (or bus). At this node the power could be generated or consumed. There are also transformers to change of voltage level for instance.

A more detailed description of the line could the following:

![Figure 2-2: Schema of a line [11]](image)

Where $Z$ is the impedance per km

$Y$ is the shunt admittance per km

2.1.2. Power flow calculation

As written above, the important point of the network management is to be able to estimate the repartition of the flows in the network in a normal situation or when an incident occurs. The current method to determine the voltage magnitude and the voltage angle at all nodes in a network is called load flow. Indeed the knowledge of these parameters is sufficient to determine the system state, which means all the other quantities like line loadings, line losses…

Depending of which quantities are known, the nodes could be modeled in 3 different ways:
- PQ-node (or Load node): the net generated active and reactive powers are known.
- PU-node (or Generator node): the net active power as well as the voltage magnitude is known.
- U0-node (or Slack-node): the voltage magnitude and the voltage angle are known. There is only one slack-node in each system (the voltage angle is chosen as a reference angle, and is often equal to 0°)

Here are presented some recalls concerning the load flow calculations. These calculations will be automatically performed in the implementation part (chapter 3 and 4) thanks to computer programs. However it is interesting to come back in details to the different steps and hypotheses.
Considering the admittance matrix
\[ Y_{bus} \text{ with } \sum Y_{kk} \text{ is the sum of all the admittances connected to the node } k \]
\[ Y_{ik} \text{ is equal to the admittance between the node } i \text{ and the node } k \]
\[ \mathbf{I} = Y_{bus} \mathbf{V} \text{ with } Y_{bus} = G_{bus} + jB_{bus} \]

The active and reactive power at the node \( i \) could be expressed as described in equations 2-1:
\[ P_i = P_{Gi} - P_{Di} = \text{Re} \left( \mathbf{V}_i \mathbf{I}_i^\ast \right) = V_i \sum_{k=1}^{n} V_k \left[ G_{ik} \cos(\theta_{ik}) + B_{ik} \sin(\theta_{ik}) \right] \]
\[ Q_i = Q_{Gi} - Q_{Di} = \text{Im} \left( \mathbf{V}_i \mathbf{I}_i^\ast \right) = V_i \sum_{k=1}^{n} V_k \left[ G_{ik} \sin(\theta_{ik}) - B_{ik} \cos(\theta_{ik}) \right] \]

Equations 2-1

In order to determine the unknown variables, two different approaches could be used:

- The Newton-Raphson approach, by using the Jacobian of the system as described in [3]:
  \[ H_{kj} = \frac{\partial P_k}{\partial \theta_j} \text{ with } \begin{cases} k \neq \text{slack node} \\ j \neq \text{slack node} \end{cases} \]
  \[ N_{ij} = \frac{\partial P_k}{\partial V_j} \text{ with } \begin{cases} k \neq \text{slack node and PU node} \\ j \neq \text{slack node and PU node} \end{cases} \]
  \[ J_{kj} = \frac{\partial Q_k}{\partial \theta_j} \text{ with } \begin{cases} k \neq \text{slack node and PU node} \\ j \neq \text{slack node} \end{cases} \]
  \[ L_{ij} = \frac{\partial Q_k}{\partial V_j} \text{ with } \begin{cases} k \neq \text{slack node and PU node} \\ j \neq \text{slack node and PU node} \end{cases} \]

After determining the variation of power, it is easy to update the vector of voltages and angles. Then the calculations are iterated with the new values of voltages and angles, until the final value is obtained.

- An approach with additional approximations, called approximations of the direct current:
  \[ V_i \approx 1 \text{ (considering that all the quantities have been converting in per-unit)} \]
  \[ |G_{ik}| \ll |B_{ik}| \]
  \[ \theta_{ik} = \theta_i - \theta_k \text{ is small} \]
  \[ b_{ik} \ll b_{ik} \]

Then the Jacobian becomes
\[ \text{Jac} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \]

with:
\[ \begin{cases} H_{kj} \approx -B_{kj} & \text{for } k \neq j \\ L_{kj} \approx -B_{kj} & \text{for } k = j \end{cases} \]
\[ H_{kk} \approx -B_{ii} \]
\[ L_{kk} \approx -B_{ii} \]

Then thanks to the equation 2-1 it is easy to compute the requested quantities.
2.2. *… to electricity market*

2.2.1. **Organization of the electricity market**

As illustrated in the figure 2-3, the electricity market is an arrangement to transfer electric energy from generating companies to consumers. The electricity market has both a technologic and an economic aspect. On one hand the power system ensures that the consumers receive the power they need, on the other hand the players who are using electricity should pay for the generation of the energy.

![Figure 2-3 : Electricity market](image)

As explained in [4], it is possible to describe the different players which may have a role in an electricity market:

**Producers and consumers:**
They appear in the three sectors described in the figure 2.3 (i.e. Grid tariffs, Power system, Electricity trading). Indeed both producer and consumer have to pay their connection to the grid. Then the producer is the one which owns and operates the power plants, while the consumer is the one which finally consumes the electricity and pays the producer for its energy production through the electricity trading.

**Retailers:**
They purchase electricity for consumers who do not want to purchase directly from producer or power exchange. They are only involved in the trading part.

**System operator:**
There is a need for a system operator which maintains the safety of the power system and is in charge of transmitting operationally the power over the grid, from the generators to the load buses. As such, it is responsible for power quality. The system operator is also technically responsible for the balance between generation and consumption. For that purpose, the generating companies put at its disposal special balancing offers (increase or reduction of generation), which it can activate if necessary. Finally, it may be in charge of buying electricity to cover losses in the grids. The fairness of trade requires the system operators to be fully independent from generating companies or consumers. Therefore it is often referred to as Independent...
System Operator (ISO) or Transmission System Operator (TSO) when it is also the owner of the transmission grid (which is often the case in Europe).

**Balance Responsible:**
While the system operator is technically responsible of the physical balance between generation and consumption as a whole, all producers, consumers and traders are required to be balance responsible for their injection and supply contracts (or they can transfer the responsibility to another player which would be responsible on their behalf). Indeed it is impossible to ensure in real time that the amount of electricity extracted from the grid by a customer corresponds to its supplier’s injections. Therefore, unbalances occur that are compensated by the TSO, via the balancing mechanism, inducing extra-costs. Thus actual energy transfers must be accounted in the electricity metering system, to ensure that the deviations will be billed to the players who actually originated them.

**Grid owners:**
The grid owner builds and maintains the grids.

### 2.2.2. The construction of the European electricity market

Until the end of the 20th century, most of the countries have their electricity generation, transport and distribution companies organized as vertically integrated monopoly. For instance in France EDF was organized as a state monopoly of generation, transport and distribution of electricity until 2000.

The setting up of an internal electricity market got under way at the end of the 1980s. From the 90s some countries opened their electricity market. As a consequence of the market opening more and more countries have decided to part the activities of commercialization and generation from the activities of transmission realized by the Transmission grid operators which have to guarantee the free, fair and non-discriminatory access to the VHV grid for the generating companies and consumers.

After a directive about “Electricity Transit”, then one on the “Transparency of Prices”, a first directive concerning the “Deregulation of the Electricity Market” was adopted in 1996 [5]. It obliged the member states to open up at least 35% of their market to competition no later than 2003, by making the major industrial consumers eligible to choose their electricity supplier.

Then the liberalization process continued in 2003 with a second directive. This directive laid down the definitive schedule for the full opening of the Internal Electricity Market: all consumers, except residential customers, would become eligible no later than the 1st of July 2004. The opening to competition for all consumers will become effective no later than the 1st of July 2007.

The building of a real integrated European market rather than a simple juxtaposition of national markets must enable to consolidate the concurrency by increasing the number of participants.
2.2.3. The cross-border exchanges

In theory if the cross-border trading is not hampered, despite the diversity of the national generation mixes, the competition must imply a convergence of the prices to a unique value with very important trading exchanges.

In practice the exchange capacities between the countries are limited, because historically they have been planned in a helping goal and not a trading one. That is why the European market is often split up in regional markets with different prices which depend on local conditions. In this case the interconnections are told “commercially congested”.

2.2.3.1. Allocation mechanisms

In spite of their limited quantities, the cross-border capacities have a notable marginal impact on the process of price elaborations. That is why it seems important to describe the different methods of allocation.

The economical theory indicates that in order to maximize the social surplus a rare resource must be attributed to the most bidding. That is why the European rules only enable the allocation of capacities thanks to auctions. As described in [6] and [7], two kinds of auctions are commonly used:

- It could be explicit auctions for which the product put on the market is a right to plan an exchange on a given contract path. In that case the TSOs on both sides of the concerned border organize common or separated auctions where the ATC are allocated. If the available capacity is insufficient to meet the demand, the concerned TSOs receive a congestion income. This income shall be used, either to increase cross-border capacity by building new lines, or to finance the eventual action of redispachting to ensure firmness of transactions (i.e. fulfillment of the contract even in case of insufficient real time capacity), or to reduce the grid access tariff. The purchased right are equivalent to capacity reservations, but the actors are not forced to use the purchased capacity. Indeed it is only after the day-ahead spot markets that the actor nominates its definitive position.

- It could be implicit auctions for which the allocations capacities are combined with the functioning of an organized electricity market thanks to a process of market coupling which optimizes the global exchanges between the different prices‘ zones. This method of allocations seems to have a lot of advantages compared to the previous one, for example:
  
  - A bigger economical efficiency
  - A greater simplicity for the participants
  - It implies the decrease of the "market power" as nobody could purchase individual rights before the electricity market.

The current repartition of these different types of allocation is illustrates in the figure 2-4:
Today the explicit auctions are widely the majority in the continental Europe while implicit auctions are present in Nordpool with the market splitting and are now present between France, Belgian and Netherlands with the trilateral market coupling. Despite the names, these two sorts of implicit allocations yield identical results in the presence of identical starting hypothesis. The difference comes from the algorithms used:

On one hand the market coupling consists in a coupling of N markets, according to a decentralized approach, resulting in a unique virtual market as long as the interconnections capacities are not saturated.

On the other hand the market splitting is at the beginning one market which is split in N independent virtual markets when the capacities are saturated.
2.2.3.2. Day-Ahead Planning

In order to have a good understanding how the reference case is chosen in chapter 3, it is important to present briefly the planning of the nominations which are made in D-1, as shown in table 2-1.

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7h30-8h30</td>
<td>Periodic nomination (yearly, monthly,…) per border</td>
</tr>
<tr>
<td>9h</td>
<td>Publication of the Day-ahead auctions specifications</td>
</tr>
<tr>
<td>10h</td>
<td>Publication of the Day-ahead ATC</td>
</tr>
<tr>
<td>11h15</td>
<td>Result of the Day-ahead auctions</td>
</tr>
<tr>
<td>13h30-14h30</td>
<td>Results of the Market coupling (automatic nomination)</td>
</tr>
<tr>
<td>19h</td>
<td>Day-ahead nominations (per border)</td>
</tr>
<tr>
<td></td>
<td>Calculation of the intra-day capacity</td>
</tr>
</tbody>
</table>

Table 2-1: Day-ahead planning

2.2.3.3. Current method based on ATC

To express the cross-border congestion, the transfer limits which are currently used are the NTC (Net Transfer Capacity) and the ATC (Available transfer Capacity) [8].

- The NTC correspond to the maximal exchange which can be realized between 2 zones electrically connected. This quantity is updated as long as we come closer to the real time in order to take in account new events.

- The ATC is the available capacity for a given period of time (year, month, day…).

![Figure 2-5 : NTC & ATC](image)

The major steps of the ATC determination are:

- Choice of a base case which is as closer as possible to the situation which has to be represented.
- Calculation of the physical margin.
- Utilization of the physical margin to maximize the exchanges. This gives the NTC.
- Repartition of the NTC in ATC by considering the different time horizons.

Although the ATC calculation is easy for an electrical peninsula, it becomes complex if the cross-border network is meshed, which is the case for the European network. Indeed in a meshed network the physical flows and the induced exchanges are very different.
For instance if an exchange of 1000 MW between France and Germany is considered, as illustrated by the figure 2-6, it is easy to notice that the exchanges France ⇒ Belgium (Fr ⇒ Be) and France ⇒ Germany (Fr ⇒ De) are competing.

By considering an example of [9], the exchange Fr ⇒ De has an influence of 15% on the flow of the line Avelin-Avelguem, situated between France and Belgium, while the exchange Fr ⇒ Be has an influence of 35%. Thus, if 100 MW of physical margin are available, several repartitions are possible:

- Increase the exchange Fr ⇒ Be of 288 MW (288MW*0,35=100MW) and the exchange Fr ⇒ De of 0MW.
- Increase the exchange Fr ⇒ De of 667 MW (667MW*0,15=100MW) and the exchange Fr ⇒ Be of 0MW.
- Or 100MW for Fr ⇒ Be and 434 MW for Fr ⇒ De

Finally the NTC published individually for each border depend on each other. Thus when the NTC on Fr ⇒ Be is increased:

- It is at the expense of the NTC on Fr ⇒ De or Fr ⇒ Ch (France ⇒ Switzerland)
- But it could increase the NTC De ⇒ Ch

As illustrated with the previous example, there is infinity of possible choices for the set of ATC. Thus it is necessary to have an optimal criterion. According to the European regulation the only legitimate criteria is the maximization of the market value of the cross-border exchanges. Unfortunately this market value is directly linked with the difference of spot price between two areas which will be known only after the actions of the organized markets.
Thus as explained in [9], the TSO have to make assumption concerning the price differential and when the estimation is wrong the market value could be very far from the optimal one.

The only possibility to remove this problem of underoptimization is to stop to allocate the capacity on each contract path separately. Thus it is necessary to change of point of view, which means not to reason with ATC.
Chapter 3.

Theoretical approach of the flow-based method

The main goal of this part is to expose the theoretical aspects of the flow-based method like the mathematical equations and the definition of the variables considered, as described in [10]. Additionally, this theoretical approach has also for goal to enable the reader to have a global comprehension before beginning the implementation part which will be possible thanks to a simple example developed in [9] which will complete the theoretical presentation and will enable the reader to have a simple practical vision of the method.

3.1. General principles

One of the goals of the flow-based method is to enable a transparent management of the network which would be as close as possible to the real time. That is why the model illustrates as simply as possible the flow constraints which could appear on the network for one group of commercial exchanges and follows the following hypothesis:

- It is a linear representation of the reality, equivalent to the approximation of the direct current.
- Each balanced area is considered as a hub linked with the neighboring hubs by some border interconnections with limited capacities. The notion of hub expresses here two main ideas:
  - Each balanced area takes care of its internal constraints.
  - The data which arise from the commercial exchange between the control areas are enough to determine the physical flows at the interconnections.

Thanks to these hypotheses the network can be modeled by a group of inequalities which depend linearly on the balances of each hub. If all the inequalities are respected then the security of the network is guaranteed, i.e. each flow of the network is inferior to its corresponding minimal flow and superior to its corresponding maximal flow.

3.2. Reference Network

The reference network is strictly defined by:

- A list of all the nodes and links (lines, transformers, phase shifter etc.)
- A list of the different areas and their composition
- The nodal topology (which line is connected with which nodes?)
- The nodal voltages
- The node injection and consumption
- The impedance of the lines (lines, transformers, phase shifters…)
- The transformer ratios
- The maximal and minimal angles for the phase shifter and their number of plots.
- A slack node
3.3. **Base case**

For all the capacity calculations the objective is to determine the available capacity for a change of cross-border exchanges. Thus by construction the results obtained are very strongly linked to the base case chosen which must represent the best anticipation of the situation.

3.4. **List of the critical branches**

Indeed as written in chapter 1 the commercial exchanges cannot compromise the network security. For a capacity study the only constraints which will be detected are the flow constraints. Thus a critical branch represents a line of the network which could probably limit the commercial exchanges between the areas because it reaches often its physical limits.

To have a progressive approach, three different models (more and more detailed) will be described. The model which will be used later in the report will be the last one which combines all the characteristics of the previous ones and is the most detailed.

3.4.1. **Model limited to the interconnections**

In this case the only factors of limitation are the interconnections between the different areas. The internal constraints (in the standard conditions of operation or if there is one fault in the network) are considered as covered by the internal redispatching.

By definition an interconnection is composed of the branches which link two areas. Here the direction of the exchange is explicitly described in the definition of the critical branches. An interconnection is a composite branch which aggregates several simple branches.

3.4.2. **Detailed model with internal branches**

In this model the network is also described more precisely:
- The interconnections are detailed branch by branch.
- The internal branches which limit the exchanges are described.

3.4.3. **Third model with recognition of the system’s contexts**

In this third part the context with one fault or more is described. A critical branch is here described as an oriented branch associated with a fault. A state of the network which corresponds to the reference state after the application of a fault is called N-1 context and the reference state is the N-0 context.

Consequently an element of the network can appear more than one time in the list of the critical branches: if two directions are critical, or if this element is critical for more than one context.

3.4.4. **General model and illustration**

The mathematical formulas reached by all the different models described previously can perfectly be matched together, as shown in figure 3-1. In this figure all the different notions described before are represented:
- The simple interconnections like A1-B1 and B1-A1
- The composite interconnections like “Comp BC” which contains the simple branches B3-C1 and B5-C4.
- The internal critical branches like A2-A3
- The representation of the different contexts. For instance if a fault appears on the branch C1-B3 the branch A3-A1 is a critical branch.

![Diagram of composite interconnections](image)

**Figure 3-1: Critical branches, general model**

### 3.4.5. Composition matrix

An easy way to link the composite branches and the simple branches is to introduce the composition matrix. An element of this matrix represents the belonging of a simple branch to a composite one, as shown in the Figure 3-2. For instance to represent the composite branch “Comp BC” there are two ones in the columns which correspond to the branches B3-C1 and B5-C4.
### 3.4.6. Application

Here we will consider the example develops in [10]. As explained above the interconnections are described as critical branches. As shown in the table, there are also three internal branches which are considered as critical branches in the N context which is, as I explained before, the normal context without incident. Concerning the N-1 context two different situations are described:

- If the branch A4-C7 are disconnected, which corresponds to the situation called “N-1 A4-C7”, two additional branches, A1-B1 and C2-B4, are considered as critical. This means that if a fault appears on the line A4-C7 the two critical lines would be in this context very influenced by an exchange’s variation and could probably reach their limits.

- The same analysis could be done for the N-1 situation “A1-B1” and the critical branches A4-C7, C2-B4 and B2-B8.
3.5. **Physical margins**

The physical margin will be defined only for each critical branch. It measures the acceptable flow variation in a critical branch (which depends on the orientation of the line). It is equal to the difference between the maximal flow and the reference flow.

### 3.5.1. Reference flows

For each context of the system, the reference flows are obtained thanks to a load flow calculation:

- The flows are calculated for the simple branches and are deduced directly from the values obtained by the load flow. This repartition calculation is made for the N situation but also for the N-K situation.
- The flows on the critical branches are obtained by aggregating the values of the simple branches thanks to the composition matrix.

### 3.5.2. Maximal flows

The maximal flows can be obtained in several ways according to the nature of the available data and the temporal view.

Generally the evaluation is directly made by using reference data: the maximal flows on the simple branches can be directly deduced from the limit used for the security study (for
example the current limit) by means of a possible decrease in order to include a level of incertitude or some incidents in the parts of the network which are not represented. Then the maximal flows on the critical branches are obtained by aggregating each simple branch thanks to the composition matrix.

### 3.5.3. Application

By considering the list of critical branches in our example, the following table could be drawn, with

\[
\Phi_M = F_{\text{Max}} - F_{\text{Ref}} \quad \text{Equation 3-1}
\]

where

- \( \Phi_M \) is the physical margin
- \( F_{\text{Ref}} \) is the reference flow
- \( F_{\text{Ref}} \) is the maximal flow

<table>
<thead>
<tr>
<th>Situation</th>
<th>Critical branches</th>
<th>Fref</th>
<th>Fmax</th>
<th>( \Phi_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>A1-&gt;B1</td>
<td>243</td>
<td>300</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>N-1 A4-C7</td>
<td>A1-&gt;B1</td>
<td>275</td>
<td>300</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>B1-&gt;A1</td>
<td>-275</td>
<td>300</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>B4-&gt;C2</td>
<td>196</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>C2-&gt;B4</td>
<td>-196</td>
<td>200</td>
<td>396</td>
</tr>
<tr>
<td>N-1 A1-B1</td>
<td>B2-&gt;B8</td>
<td>-153</td>
<td>300</td>
<td>453</td>
</tr>
<tr>
<td></td>
<td>B8-&gt;B2</td>
<td>153</td>
<td>300</td>
<td>147</td>
</tr>
<tr>
<td></td>
<td>B4-&gt;C2</td>
<td>68</td>
<td>200</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>C2-&gt;B4</td>
<td>-68</td>
<td>200</td>
<td>268</td>
</tr>
<tr>
<td></td>
<td>A4-&gt;C7</td>
<td>12</td>
<td>300</td>
<td>288</td>
</tr>
<tr>
<td></td>
<td>C7-&gt;A4</td>
<td>-12</td>
<td>300</td>
<td>312</td>
</tr>
</tbody>
</table>

Table 3-2 : Calculation of the physical margins

### 3.6. Generation shift keys

A supplementary exchange between two areas has the following consequences:
- An increase of the generation in the export’s area
- An decrease of the generation in the import’s area

This zonal vision is insufficient for the TSOs because the network calculations bring into play the nodal injections. Thus the TSOs need to know which generators will be implied and the volume of production associated.

Generally this repartition of the generation is determined thanks to constant coefficients, also called Generation Shift Keys (GSK), which link the variation of the zonal balance and the variation of injection for each node.
3.6.1. List of the participating nodes

A participating node represents a node where the injection varies significantly during a variation of the zonal balance in which this node is defined. The TSOs will assess the GSK for these very nodes.

3.6.2. Definition of the GSK

As written above, the Generations Shift Keys are defined for all the participating nodes. They represent the estimated effect of an increment of the zonal balance on the algebraic injection of the node. Approximately the GSK represent the forecasted merit-order for the price zone.

By definition for a price zone the sum of the GSK is equal to 100%.

The GSK are classified in a matrix where the columns are indexed by the price zone and the row by the participating nodes. For the example presented in this part the GSK matrix is the following:

\[
\begin{bmatrix}
1 & 4 & 7 & 6 & 7 \\
A & 28\% & 0 & ... \\
A_4 & 28\% & 0 & ... \\
A_7 & 44\% & 0 & ... \\
... & ... & ... & ... \\
B_6 & 0 & 60\% & ... \\
B_7 & 0 & 40\% & ... \\
... & ... & ... & ... \\
\end{bmatrix}
\]

Figure 3-4: GSK matrix

How could these coefficients be interpreted? For instance, by considering an increase of balance in zone A, the influence of this increase on the generations could be interpreted as follows:

<table>
<thead>
<tr>
<th>Node</th>
<th>Coeff.</th>
<th>Base case</th>
<th>Zone A +100MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>28%</td>
<td>571</td>
<td>599</td>
</tr>
<tr>
<td>A4</td>
<td>28%</td>
<td>571</td>
<td>599</td>
</tr>
<tr>
<td>A7</td>
<td>44%</td>
<td>858</td>
<td>902</td>
</tr>
<tr>
<td>Prod A</td>
<td>100%</td>
<td>2000</td>
<td>2100</td>
</tr>
</tbody>
</table>

Table 3-3: Illustration of GSK signification

\[
28\% = \frac{571}{2000} \times 100
\]

If the balance of zone A increases of 100 MW then the generation at node A1 increase from 571 MW to 599 MW which means an increase of 28 MW (28%×100MW).
3.7. **Relation between the physical flows and the exchanges**

3.7.1. **Influence of the injections: the nodal PTDF matrix**

Based on a state of the initial network, the influence on the flow on a critical branch of every additional MW injected at a participating node is called the Power Transfer Distribution Factor (PTDF).

With the approximation of the Direct Current the PTDF only depend on the characteristics of the branches and the network topology:

- If the study is limited to the interconnections the PTDF are only calculated according to the state \( N \).
- If the contexts of the system are introduced, the topology varies along with the context. That is why the PTDF must be calculated for each context where the critical branch appears.

3.7.1.1. **Calculation of the nodal PTDF:**

- **\( N \) context:**

  ![Figure 3-5: N state](image)

  Let \( \mathbf{F}_{j\rightarrow k}^{\text{Ref}} \) be the flow of the branch \( j \rightarrow k \) in the reference state.

  Let \( \mathbf{F}_{j\rightarrow k} \) be the flow of the branch \( j \rightarrow k \) after the injection of 1 MW at node \( i \) (and compensation at the hub).

  The expression of the nodal PTDF \( \alpha_{j\rightarrow k} \), which means the influence of the injection of 1 MW at node \( i \) on the branch \( j \rightarrow k \) is:
\[ \alpha_{j\rightarrow k}^{'} = \frac{F_{j\rightarrow k}^{'} - F_{j\rightarrow k}^{\text{Ref}}}{1} \quad \text{Equation 3-2} \]

- **N-1 context:**

![Figure 3-6: N-1 state (disconnection of the pq branch)](image)

- **First approach**

  The same calculation as previously could be performed by considering the reference state as the one with the disconnection of the line \( p\rightarrow q \).

- **Second approach**

  It is also possible to express the nodal PTDF as a function of nodal PTDF in the N context, as developed in the appendix 1:

  Let \( \tilde{\alpha}_{jk,i} \) be the PTDF of the line \( j\rightarrow k \) after the disconnection of the line \( p\rightarrow q \):

  \[
  \tilde{\alpha}_{jk,i} = \alpha_{jk,i} + \alpha_{pq,i} \times \frac{\alpha_{jk,p} - \alpha_{jk,q}}{1 - (\alpha_{pq,p} - \alpha_{pq,q})} \quad \text{if} \ jk \neq pq
  \]

  \[
  \tilde{\alpha}_{pq,i} = 0
  \]

  \text{Equations 3-3}

**3.7.1.2. Computation of the nodal PTDF matrix**

By using the individual PTDF the corresponding matrix can be built:
- Each couple of critical branch and participating node is studied sequentially
- The calculations are made according to approximation of the Direct Current
- The additional injection is always compensated at the slack node.
- Each context of the system is considered individually.
The table 3-4 shows how the PTDF matrix looks like:

<table>
<thead>
<tr>
<th>Critical branches</th>
<th>Participating nodes Zone A</th>
<th>...</th>
<th>Participating nodes Zone C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A3</td>
<td>...</td>
</tr>
<tr>
<td>A1-&gt;B1/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>A2-&gt;A3/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>A4-&gt;C2/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>B1-&gt;A1/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>CompBC/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>CompCB/1_</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>A2-&gt;A3/A1-A2</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>A2-&gt;C1/A1-A2</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>A3-&gt;A1/C1-B3</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
<tr>
<td>CompRS/C1-B3</td>
<td>ptdf</td>
<td>ptdf</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 3-4: Illustration of the PTDF matrix

3.7.2. From the injections to the exchanges

It is often easier to work with a relation between the flows and the exchanges instead if the one between the flows and the injections.

By using the GSK matrix a relation between the critical branches and the exchanges can be deduced.

Zonal PTDF

\[
\begin{pmatrix}
\text{ptdf}^A_{\text{branch 1}} & \ldots & \text{ptdf}^Z_{\text{branch 1}} \\
\vdots & \ddots & \vdots \\
\text{ptdf}^A_{\text{branch p}} & \ldots & \text{ptdf}^Z_{\text{branch p}}
\end{pmatrix}
\]

Nodal PTDF

\[
\begin{pmatrix}
\text{ptdf}^\text{node 1}_{\text{branch 1}} & \ldots & \text{ptdf}^\text{node q}_{\text{branch 1}} \\
\vdots & \ddots & \vdots \\
\text{ptdf}^\text{node 1}_{\text{branch p}} & \ldots & \text{ptdf}^\text{node q}_{\text{branch p}}
\end{pmatrix}
\]

GSK

\[
\begin{pmatrix}
\text{gsk}^\text{zone A}_{\text{node 1}} & \ldots & \text{gsk}^\text{zone Z}_{\text{node 1}} \\
\vdots & \ddots & \vdots \\
\text{gsk}^\text{zone A}_{\text{node q}} & \ldots & \text{gsk}^\text{zone Z}_{\text{node q}}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\text{ptdf}^A_{\text{branch 1}} & \ldots & \text{ptdf}^Z_{\text{branch 1}} \\
\vdots & \ddots & \vdots \\
\text{ptdf}^A_{\text{branch p}} & \ldots & \text{ptdf}^Z_{\text{branch p}}
\end{pmatrix}
\]

×

\[
\begin{pmatrix}
\text{ptdf}^\text{node 1}_{\text{branch 1}} & \ldots & \text{ptdf}^\text{node q}_{\text{branch 1}} \\
\vdots & \ddots & \vdots \\
\text{ptdf}^\text{node 1}_{\text{branch p}} & \ldots & \text{ptdf}^\text{node q}_{\text{branch p}}
\end{pmatrix}
\]

Equation 3-4

To obtain the Transfer PTDF matrix it only remains to subtract the columns.
\[ \begin{bmatrix} \text{Matrix} \text{Transfer}_{\text{PTDF}} \end{bmatrix} = \begin{bmatrix} \text{ptdf}_{A \rightarrow B}^{\text{branch 1}} & \ldots & \text{ptdf}_{X \rightarrow Z}^{\text{branch 1}} \\ \vdots & \ddots & \vdots \\ \text{ptdf}_{A \rightarrow B}^{\text{branch p}} & \ldots & \text{ptdf}_{X \rightarrow Z}^{\text{branch p}} \end{bmatrix} = \begin{bmatrix} \text{ptdf}_{A}^{\text{branch 1}}_A - \text{ptdf}_{B}^{\text{branch 1}}_B & \ldots & \text{ptdf}_{X}^{\text{branch 1}}_X - \text{ptdf}_{Z}^{\text{branch 1}}_Z \\ \vdots & \ddots & \vdots \\ \text{ptdf}_{A}^{\text{branch p}}_A - \text{ptdf}_{B}^{\text{branch p}}_B & \ldots & \text{ptdf}_{X}^{\text{branch p}}_X - \text{ptdf}_{Z}^{\text{branch p}}_Z \end{bmatrix} \]

Equation 3-5

### 3.7.3. Application

By applying this definition to the parameters of the example, the following matrix is obtained:

\[
\begin{align*}
\text{Ptdf}^{A1}_{A1 \rightarrow B1} &= 0.62 \\
\text{Ptdf}^{A4}_{A1 \rightarrow B1} &= 0.82 \Rightarrow \text{Ptdf}^{A}_{A1 \rightarrow B1} = 0.62 \\
\text{Ptdf}^{A7}_{A1 \rightarrow B1} &= 0.49 \\
\text{Ptdf}^{B6}_{A1 \rightarrow B1} &= 0.35 \\
\text{Ptdf}^{B8}_{A1 \rightarrow B1} &= 0.11 \\
\end{align*}
\]

\[
\Rightarrow \text{Ptdf}^{A \rightarrow B}_{A1 \rightarrow B1} = 0.42
\]

\[
\begin{bmatrix}
\Delta F_{N, A1 \rightarrow B1} \\
\Delta F_{N, A2 \rightarrow B3} \\
\vdots \\
\Delta F_{N \rightarrow A1 \rightarrow B1, B4 \rightarrow C2}
\end{bmatrix} = \begin{bmatrix}
0.42 & 0.23 & -0.19 \\
0.23 & 0.10 & -0.13 \\
\vdots & \vdots & \vdots \\
-0.35 & 0.13 & 0.47
\end{bmatrix} \times \begin{bmatrix}
\Delta E_{A \rightarrow B} \\
\Delta E_{A \rightarrow C} \\
\Delta E_{B \rightarrow C}
\end{bmatrix}
\]

### 3.8. List of the participating phase shifting transformers

The list of the participating phase shifters is a sublist of the phase shifters defined in the reference case and is made of those which have a significant impact on the physical flow at the interconnections.

### 3.9. Influence of the phase shifters: phase shifter factors

In the same way as the PTDF the Phase Shifter Factor (PSF) is the influence on the flow of a critical branch if the plot of a participating phase shifter is increased by 1 degree. Then the PSF matrix can be built, according to the following hypothesis:

- Each couple of critical branch and participating transformer is studied sequentially.
- The calculations are made according to approximation of the direct current.
- Each context of the system is considered individually.
3.10. Flow-based parameters

In this part the flow-based parameters will be computed. They will be presented differently according to the context in order to have accurate parameters, i.e.:

- On one hand the zonal PTDF and the vector of border capacity.
- On the other hand the transfer matrix for the option and the obligations and the vector of border capacity.

3.10.1. Border capacity vector

The total flow in each critical branch is the sum of 4 different terms:

- The reference flows \( F_{\text{Ref}} \).
- The flow’s increments \( \Delta F_{\text{PS}} \) related to the effective position of the participating phase shifters (if the position is different to the reference position).
- The flow’s increments \( \Delta F_{\text{DFP}} \) related to the transactions which are not nominated yet and for which the feasibility has to be tested.

To ensure the security of the network the total flows must be lower than the maximal flows, as illustrated in equation 3-8.

\[
\begin{bmatrix}
F_{B_{1t}} \\
\vdots \\
F_{B_{P}}
\end{bmatrix} = \begin{bmatrix}
F_{\text{Ref}}_{B_{1t}} \\
\vdots \\
F_{\text{Ref}}_{B_{P}}
\end{bmatrix} + \begin{bmatrix}
\Delta F_{B_{1t}}^{\text{PS}} \\
\vdots \\
\Delta F_{B_{P}}^{\text{PS}}
\end{bmatrix} + \begin{bmatrix}
\Delta F_{B_{1t}} \\
\vdots \\
\Delta F_{B_{P}}
\end{bmatrix} \leq \begin{bmatrix}
F_{\text{Max}}_{B_{1t}} \\
\vdots \\
F_{\text{Max}}_{B_{P}}
\end{bmatrix}
\]

Equation 3-7

Another formulation is to rewrite the inequality as a function of the new physical margin, as shown in the equation 3-9.
Application on the example:

\[
\begin{bmatrix}
\Delta E_{A \rightarrow B} \\
\Delta E_{A \rightarrow C} \\
\Delta E_{B \rightarrow C}
\end{bmatrix} = \begin{bmatrix}
10 \\
20 \\
50
\end{bmatrix}
\]

be the variation of exchanges.

The physical margin becomes after the increase of the exchanges:

\[
\begin{bmatrix}
\Phi_{M \ br1} \\
\Phi_{M \ bop}
\end{bmatrix} = \begin{bmatrix}
F_{i \ br1}^{\text{Max}} \\
F_{i \ bop}^{\text{Max}}
\end{bmatrix} - \begin{bmatrix}
F_{br1} \\
F_{bop}
\end{bmatrix} \geq 0
\]

with

\[
\begin{bmatrix}
\Delta F_{br1} \\
\Delta F_{bop}
\end{bmatrix} = \text{Matrix}^{\text{Transfer}} \times \begin{bmatrix}
\Delta E_{A \rightarrow B} \\
\Delta E_{A \rightarrow C} \\
\Delta E_{B \rightarrow C}
\end{bmatrix}
\]

Table 3-5 : New margin after exchanges

All the physical margins are positive except for the branch B4-C2. Thus the proposed exchanges do not ensure the security of the network, they must be rejected.

3.10.2. Obligation Transfer matrix

The numerical values for the nodal PTDF and the zonal PTDF depend on the choice of the slack node. In practice, what is interesting is the physical flows caused by the exchange between an area X and an area Y. Thanks to the linearity of the model these values are independent of the balance node which is only an intermediary point in the calculation. The obligation matrix \( M^{\text{Oblig}}_{\text{PTDF}} \) is built by considering the Transfer PTDF, as written in equation 3-8.
If the allocated rights are obligations, this matrix is used to verify the simultaneous feasibility of a set of obligations in the following way:

- The resulting exchange vector is built.
  \[
  \Delta E = \begin{bmatrix}
    \Delta E_{A\Rightarrow B} & \Delta E_{A\Rightarrow C} & \ldots & \Delta E_{B\Rightarrow A}
  \end{bmatrix}
  \]

- The set is validated only if the exchange vector verifies, as expressed in equation 3-12.
  \[
  \Delta F = M_{PTDF}^{Oblig} \Delta E^T \quad \text{Equation 3-11}
  \]

Finally the inequality, which ensures that the network is secured, is the equation 3-13.

\[
\Phi_{M_{br1}} = \left[ \begin{array}{c}
F_{max}^{br1} \\
\vdots \\
F_{max}^{brp}
\end{array}\right] - \left[ \begin{array}{c}
F_{Ref}^{br1} \\
\vdots \\
F_{Ref}^{brp}
\end{array}\right] + \left[ \begin{array}{c}
\Delta F_{br1} \\
\vdots \\
\Delta F_{brp}
\end{array}\right] \geq 0 \quad \text{Equation 3-12}
\]

### 3.10.3. Option transfer matrix

The rights considered here are options which that the volume of the transaction could be lower than the volume of the right. To take into account this risk, the flows which will be considered are the incremental flows which bring the system closer of its limits and not the flows which take away the system.

To apply this, an option transfer matrix is introduced with the following hypothesis:

- All the elements of the matrix are greater than or equal to zero (else a negative incremental flow on a critical branch could exist while the exchange vector would be positive).
- An element of the matrix is equal to the corresponding element in the obligation transfer matrix in order to have, the same decrease of physical margin in the two cases for every positive transactions.

These two hypotheses can be rewritten:

\[
M_{Transfer}^{Option} = \left[ \max(m_{ij}, 0) \right] \quad \text{with} \quad M_{Transfer}^{Oblig} = \left[ m_{ij} \right] \quad \text{Equation 3-13}
\]

The feasibility of a set of options is tested as follows:

- The resulting exchange vector is built.
  \[
  \Delta E = \begin{bmatrix}
    \Delta E_{A\Rightarrow B} & \Delta E_{A\Rightarrow C} & \ldots & \Delta E_{B\Rightarrow A}
  \end{bmatrix}
  \]

- The set is validated only if the exchange vector verifies the equation 3-15.
\[ \Delta F = M_{\text{Transfer}}^\text{Option} \Delta E^T \]  \hspace{1cm} \text{Equation 3-14}

Finally the inequality, which ensures that the network is secured, is:

\[
\begin{bmatrix}
\Phi_M^{b1} \\
\vdots \\
\Phi_M^{bp}
\end{bmatrix}
= 
\begin{bmatrix}
F_{\text{Max}}^{b1} \\
\vdots \\
F_{\text{Max}}^{bp}
\end{bmatrix}
- 
\begin{bmatrix}
F_{\text{Ref}}^{b1} \\
\vdots \\
F_{\text{Ref}}^{bp}
\end{bmatrix}
+ 
\begin{bmatrix}
\Delta F_{\text{b1}} \\
\vdots \\
\Delta F_{\text{bp}}
\end{bmatrix}
\geq 0 \hspace{1cm} \text{Equation 3-15}
\]

3.11. Explicit day-ahead auctions

Here is described the optimization problem which is solved by considering explicit auctions:

- The bids are defined by the contractual path, the volume and the price.
- The aim of the optimization is to maximize the market value.

The proposed products are rights to nominate exchanges. These auctions are options. Thus as explained in the paragraph 3.10.3, the following hypotheses are applied:
- The contractual path \( A \Rightarrow B \) and \( B \Rightarrow A \) are treated separately.
- The negative transfer PTDFs are replaced by zero (else a negative incremental flow on a critical branch could exist while the exchange vector would be positive).

The security constraints are still the inequalities which specify that the physical margin need to be greater than or equal to zero.

The optimization problem is therefore formalized as follows:

\[
\text{Max} \left( \sum_k \sum_{C_{X,Y} \in S} \left( P_{X,Y}^k \times E_{X,Y}^k \right) \right) \hspace{1cm} \text{Equation 3-16}
\]

\[
\forall i \in B, \sum_{C_{X,Y} \in S} \left( m_{i,C_{X,Y}} \sum_k E_{X,Y}^k \right) \leq \Phi m_{i} \hspace{1cm} \text{Equation 3-17}
\]

where:
- \( S \) is the possible contractual paths
- \( B \) is the critical branches
- \( P_{C_{X,Y}}^k(.) \) is the proposed price by the actor \( k \) for the contr. path \( X \rightarrow Y \)
- \( E_{C_{X,Y}}^k \) is the allocated volume for the actor \( k \) on the contr. path \( X \rightarrow Y \)
- \( m_{i,C_{X,Y}} \) is the option matrix
- \( \Phi m_{b,p} \) is the physical margin on the critical branch \( p \)

Come back to the example.
We have $\Delta F = M^{\text{Option}}_{\text{Transfer}} \Delta E$

Then we can deduce the set of inequalities which describes the constraints of our problem.

<table>
<thead>
<tr>
<th>Crit.Br.</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>N 1, A1-B1</td>
<td>$0.0 \leq 42.3% \times E_{A1B} + 0.0% \times E_{B1A} + 23.3% \times E_{B1C} + 0.0% \times E_{C1A} + 19.0% \times E_{C1C} \leq 76.1$</td>
</tr>
<tr>
<td>N 1, A1-B1</td>
<td>$0.0 \leq -42.3% \times E_{A1B} + 0.0% \times E_{B1A} - 23.3% \times E_{B1C} + 0.0% \times E_{C1A} + 19.0% \times E_{C1C} \leq 523.9$</td>
</tr>
</tbody>
</table>

Table 3-6 : Explicit auctions, set of constraints

In the table 3-7 an example of set of bids is given.

<table>
<thead>
<tr>
<th>Contractual Path</th>
<th>Proposed Price</th>
<th>Requested quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>22.00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>18.00 €</td>
<td>100 MW</td>
</tr>
<tr>
<td></td>
<td>14.00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>21.77 €</td>
<td>quant. tot. 25 MW</td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>26.50 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>24.50 €</td>
<td>100 MW</td>
</tr>
<tr>
<td></td>
<td>22.50 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>24.50 €</td>
<td>quant. tot. 93 MW</td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B=&gt;C</td>
<td>2.00 €</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>1.00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>0.50 €</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>15.03 €</td>
<td>quant. tot. 0 MW</td>
</tr>
</tbody>
</table>

Table 3-7 : Explicit auctions, set of bids

After the optimization the volumes accepted are presented in the table 3-9.

<table>
<thead>
<tr>
<th>Contractual Path</th>
<th>Proposed Price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>22.00 €</td>
<td>25 MW</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>18.00 €</td>
<td>100 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>14.00 €</td>
<td>25 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>21.77 €</td>
<td>quant. tot. 25 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>26.50 €</td>
<td>25 MW</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>24.50 €</td>
<td>100 MW</td>
<td>68 MW</td>
</tr>
<tr>
<td></td>
<td>22.50 €</td>
<td>25 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>24.50 €</td>
<td>quant. tot. 93 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B=&gt;C</td>
<td>2.00 €</td>
<td>50 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>1.00 €</td>
<td>200 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>0.50 €</td>
<td>50 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>15.03 €</td>
<td>quant. tot. 0 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B=&gt;A</td>
<td>6.00 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>4.00 €</td>
<td>200 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>2.00 €</td>
<td>50 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>4.80 €</td>
<td>quant. tot. 50 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C=&gt;A</td>
<td>2.00 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>1.00 €</td>
<td>200 MW</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>0.50 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>0.00 €</td>
<td>quant. tot. 300 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C=&gt;B</td>
<td>9.50 €</td>
<td>25 MW</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>7.50 €</td>
<td>100 MW</td>
<td>41 MW</td>
</tr>
<tr>
<td></td>
<td>5.50 €</td>
<td>25 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>7.50 €</td>
<td>quant. tot. 66 MW</td>
<td></td>
</tr>
<tr>
<td>marg. Price</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-8 : Result of the optimization for explicit auctions

<table>
<thead>
<tr>
<th></th>
<th>Market value</th>
<th>4 048.50 €</th>
</tr>
</thead>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Accepted bids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Refused bids</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marginal bids</td>
<td></td>
</tr>
</tbody>
</table>

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Notification: The explanation about the calculation of the marginal prices is given in the appendix 5. The accepted quantities are rounded to the lower MW.

Additionally it is easy to verify that the auctions respect the basic principles of auctions, which means:
- The bids entirely accepted have a price greater than the marginal price.
- The bid partially accepted has a price equal to the marginal price.
- The refused bids have a price lower than the marginal price.

3.12. Implicit day-ahead auctions: market coupling

In the case of flow-based market coupling:
- The actors issue offers to sell energy on the electricity market of their injection area and/or offers to buy energy on the electricity market of their consumption area.
- The allocation of capacities is made implicitly and is combined with the clearing of the electricity market.
- The capacities are also allocated to all the accepted transactions and not to determined actors.

The criterion to be maximized is the market value.

The security constraints are still the inequalities which specify that the physical margin needs to be superior or equal to zero.

All the actors which issue an offer have to honor it. That is why the netting is possible. Thus the set of PTDF used is the zonal PTDF matrix.

Finally the optimization problem could be formalized as follows:

\[
Max \sum_{i \in Zone} \int_{0}^{q_{i}^{bid}} p_i(q) \, dq - \int_{0}^{q_{i}^{offer}} c_i(q) \, dq
\]

with
\[
\begin{align*}
q_{i}^{bid} & \geq 0 \\
q_{i}^{offer} & \geq 0
\end{align*}
\]

\[
\begin{bmatrix}
R_{br1}^A & \cdots & R_{br1}^Z \\
\vdots & \ddots & \vdots \\
R_{brp}^A & \cdots & R_{brp}^Z
\end{bmatrix}
\begin{bmatrix}
q_{i}^{offer} - q_{i}^{bid} \\
\vdots \\
q_{Z}^{offer} - q_{Z}^{bid}
\end{bmatrix}
\leq
\begin{bmatrix}
\Phi_{Mbr1} \\
\vdots \\
\Phi_{Mbrp}
\end{bmatrix}
\]

45
with:
\[
\begin{align*}
q_{i-bid} & \quad \text{accepted bids for the zone } i \\
p_{i}(\cdot) & \quad \text{price of the zone } i \\
q_{i-sup} & \quad \text{accepted offer of the zone } i \\
c_{i}(\cdot) & \quad \text{price of the zone } i \\
R_{i}^{X-p} & \quad \text{zonal pdf for the zone } X \text{ on the branch } p \\
\Phi_{Mbr-p} & \quad \text{physical margin on the branch } p \\
\end{align*}
\]

Come back to the example:

We have \( \Delta F = M_{Transfer} \Delta E \)

Then we can deduce the set of inequalities which describe the constraints of our problem

<table>
<thead>
<tr>
<th>Crit.Br.</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>A1-&gt;B1</td>
</tr>
<tr>
<td></td>
<td>0,0 \leq -42,3% \times E_{A1-B} + 23,3% \times E_{A1-C} + -19,0% \times E_{B1-C} + \leq 76,1</td>
</tr>
<tr>
<td></td>
<td>B1-&gt;A1</td>
</tr>
<tr>
<td></td>
<td>0,0 \leq -42,3% \times E_{A1-B} + -23,3% \times E_{A1-C} + 19,0% \times E_{B1-C} + \leq 523,9</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td>N-1</td>
<td>A1-&gt;B1</td>
</tr>
<tr>
<td></td>
<td>0,0 \leq -46,5% \times E_{A1-B} + 30,5% \times E_{A1-C} + -16,0% \times E_{B1-C} + \leq 50,8</td>
</tr>
<tr>
<td></td>
<td>A1-&gt;A1</td>
</tr>
<tr>
<td></td>
<td>0,0 \leq -23,7% \times E_{A1-B} + 3,0% \times E_{A1-C} + -20,7% \times E_{B1-C} + \leq 453,9</td>
</tr>
<tr>
<td></td>
<td>A1-&gt;B1</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
</tbody>
</table>

Table 3-9 : Market coupling, set of constraints

In the table 3-6 an example of set of bids is given.

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achat</td>
<td>12,00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td>sur A</td>
<td>10,00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>8,00 €</td>
<td>1 000 MW</td>
</tr>
<tr>
<td></td>
<td>40,00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td>Achat</td>
<td>29,00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td>sur B</td>
<td>12,00 €</td>
<td>1 000 MW</td>
</tr>
<tr>
<td></td>
<td>45,00 €</td>
<td>50 MW</td>
</tr>
<tr>
<td>Achat</td>
<td>36,00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td>sur C</td>
<td>10,00 €</td>
<td>500 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vente</td>
<td>7,00 €</td>
<td>50 MW</td>
</tr>
<tr>
<td>sur A</td>
<td>10,00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>20,00 €</td>
<td>400 MW</td>
</tr>
<tr>
<td>Vente</td>
<td>19,00 €</td>
<td>50 MW</td>
</tr>
<tr>
<td>sur B</td>
<td>29,00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>40,00 €</td>
<td>400 MW</td>
</tr>
<tr>
<td>Vente</td>
<td>25,00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td>sur C</td>
<td>37,00 €</td>
<td>150 MW</td>
</tr>
<tr>
<td></td>
<td>45,00 €</td>
<td>200 MW</td>
</tr>
</tbody>
</table>

Table 3-10: Market coupling, set of bids

After the optimization the quantities accepted are presented in the table 3-11.
### Table 3-11: Result of the optimization for market coupling

The table 3-7 shows how the capacities are allocated. For instance the marginal price of the zone C is 36€. Thus the accepted offers to buy have a price greater than or equal to 36€. It is the opposite for the accepted offers to sell, which have a price lower than or equal to 36 €. The other quantities presented are the market value which is equal to 5503€ and the global exchanges.

Notification: The explanation about the calculation of the marginal prices is given in the appendix 5.

Additionally it is easy to verify that the auctions respect the basic principles of auctions, which means:

The offers to buy which are
- entirely accepted have a price greater than the marginal price.
- partially accepted has a price equal to the marginal price.
- refused have a price lower than the marginal price.

The offers to sell which are
- entirely accepted have a price lower than the marginal price.
- partially accepted has a price equal to the marginal price.
- refused have a price greater than the marginal price.

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buying on A</td>
<td>12.00 €</td>
<td>25 MW</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>10.00 €</td>
<td>200 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>8.00 €</td>
<td>1 000 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Tot. quant.</td>
<td>25 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>marg. Price</strong></td>
<td>10.00 €</td>
<td>balance A</td>
<td>153 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling on A</td>
<td>7.00 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>10.00 €</td>
<td>200 MW</td>
<td>128 MW</td>
</tr>
<tr>
<td></td>
<td>20.00 €</td>
<td>400 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Tot. quant.</td>
<td>178 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buying on B</td>
<td>40.00 €</td>
<td>25 MW</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>29.00 €</td>
<td>200 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>12.00 €</td>
<td>1 000 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Tot. quant.</td>
<td>75 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>marg. Price</strong></td>
<td>29.00 €</td>
<td>balance B</td>
<td>-25 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selling on B</td>
<td>19.00 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>29.00 €</td>
<td>200 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td></td>
<td>40.00 €</td>
<td>400 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Tot. quant.</td>
<td>50 MW</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Proposed price</th>
<th>Requested quantity</th>
<th>Accepted quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buying on C</td>
<td>45.00 €</td>
<td>50 MW</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>36.00 €</td>
<td>200 MW</td>
<td>103 MW</td>
</tr>
<tr>
<td></td>
<td>10.00 €</td>
<td>500 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Tot. quant.</td>
<td>153 MW</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>marg. Price</strong></td>
<td>36.00 €</td>
<td>balance C</td>
<td>-128 MW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Exch</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A&gt;B</td>
<td>25 MW</td>
</tr>
<tr>
<td>A&gt;C</td>
<td>128 MW</td>
</tr>
<tr>
<td>B&gt;C</td>
<td>0 MW</td>
</tr>
</tbody>
</table>

**Market value**: 5 503,00 €
Chapter 4.
Studies of simple cases

The studies described in this part are made to illustrate the feasibility of the flow-based method. Indeed it seems reasonable before trying to test the reliability of the flow-based method on a big number of data to verify the behavior of the flow-based method on simple cases. This approach has also a second advantage: it enables us to compare the results of the flow-based method with the equivalent results with an ATC approach.

This part will be divided in two major studies:
- In the first part a real application will be illustrated
- In the second part focus will be on the feasibility and the comparison of the flow-based method and the ATC approach.

4.1. **Real simulation of the flow-based method with several actors**

![Zonal description of the simulation](image)

Here the context integrates the notion of European network, and the point of view of several actors. As shown in the figure 4-1 the simulation comprises four different areas between which the exchanges will be calculated. This situation where several actors collaborate for the gathering of the data and the elaboration of the results shows is a good illustration of what will be done for the future applying of the flow-based method at a European level.

The study is divided in several steps:
- Gathering the data
- Verification of the data
- Computation of the optimization problem
- Analysis of the results

4.1.1. Determination of the parameters

4.1.1.1. Given parameters

The first step is to gather the input data. Each actor has to produce his own parameter set, which is composed of:

- The list of the critical branches, in the basic context (N context) and contexts with one or several faults (N-k context).
- The corresponding reference and maximal flows in MW.
- The list of the corresponding PTDF with the list of predefined exchanges B=>A, B=>C, D=>A, D=>C.

4.1.1.2. First verification of the parameters

One of the questions which could be raised is how we can be sure that the data are all consistent. Indeed the load flow calculation and the determination of the PTDF coefficients are made separately by each actor. That is why a verification of the consistency of the data is important:

- In order to do this verification it is necessary to use the list of critical branches given by the different actors.
- Then load flow calculations are computed for all the different topologies (N and N-k i.e. by considering the faults described in the list of critical branches). After having achieved this task thanks to the internal software of RTE, the reference flows and maximal flows of all the reference branches are accessible.
- Finally the last task which has to be done is the computation of the PTDFs, still with the help of the software, where the practical calculation is:

\[
PTDF = \frac{F_{\text{Exch} + 100\text{MW}} - F_0}{100} \quad \text{Equation 4-1}
\]

The table 4-1 shows a part of the results which are very satisfactory. Indeed the results computed on RTE’s software are quite similar with the one provided by each actor.
4.1.1.3. Construction of the transfer PTDF matrix

The data include only the critical branches and the exchanges in one direction. In order to compute the entire matrix it is necessary to add the symmetrical term missing by applying some simple rules:

- For the opposite exchanges: $Ptdf_{i \rightarrow j}^{l} = -Ptdf_{j \rightarrow i}^{l}$

- For the opposite critical branches: $Ptdf_{i \rightarrow j}^{l} = -Ptdf_{i \rightarrow j}^{l'}$

4.1.1.4. Exchange and reference case

The available data do not exactly correspond to the situation that has to be studied:

- The base case has been built upon a snapshot of the European network. Therefore it is consistent in terms of exchanges with the realized values of the day and time step of the snapshot, i.e. with yearly, monthly, daily, and if any intra-daily nominations for that time.
- By contrast, the simulation will focus on day-ahead allocation, i.e. after yearly and monthly nominations.

The base case data need to be adapted to obtain the reference data. This is done by replacing the total exchanges of the reference case by the yearly and monthly nominations for the target day, as described in equations 4-2. The new reference flows will be assessed by means of the PTDFs computed on the base case.\(^1\)

---

\(^1\) One could theoretically build from scratch a state of the network consistent with the yearly and monthly nominations. But this state cannot generally be observed in real operation, and its plausibility is therefore extremely difficult to check.
\[ E_{\text{basecase}} = \text{Nom}_{\text{Yearly, basecase}} + \text{Nom}_{\text{Monthly, basecase}} + \text{Nom}_{\text{ID, basecase}} \]
\[ E_{\text{ref}} = \text{Nom}_{\text{Yearly, target}} + \text{Nom}_{\text{Monthly, target}} \]
\[ F_{\text{ref}} = F_{\text{basecase}} - \sum_{(i,j)} PTDF_{i-j} \times E_{\text{basecase}} + \sum_{(i,j)} PTDF_{i-j} \times E_{\text{ref}} \]

**Equations 4-2**

### 4.1.1.5. List of Bids

The list of bids is given in a separate file. This file includes for each bid:
- The number which identifies the bid
- The requested contract path (from zone X to zone Y)
- The expected capacity
- The proposed price

### 4.1.2. Optimization

#### 4.1.2.1. Formalization of the optimization problem

Here the goal is to simulate a day-ahead explicit auction, by considering that the allocated rights are only options. In this point of view the transfer matrix has to be modified into an option transfer matrix.

This means that all the negative values are replaced by zero.

\[ M_{\text{Option, PTDF}} = \left[ \text{Max}(0, m_{i,j}^{\text{PTDF}}) \right] \text{ Equation 4-3} \]

In an explicit auction perspective the cost function will be the linear combination between the bid price and the allocated capacity.

Thus the goal is to find \( \max \left( \sum_{k,(i,j)} p_{i \rightarrow j}^k \times q_{i \rightarrow j}^k \right) \) \text{ Equation 4-4} \]

Where \( \sum_{k,(i,j)} p_{i \rightarrow j}^k \times q_{i \rightarrow j}^k \) is called the market value.

\( q_{i \rightarrow j}^k \) is the capacity allocated to the bid k on the contract path \( i \rightarrow j \)

\( p_{i \rightarrow j}^k \) is the price in the bid k proposed on the contract path \( i \rightarrow j \)

The formalization of the optimization problem could be done as follows:
\[
\begin{align*}
\Delta F_i &= \sum_{i,j} Ptdf_i^{ij} \times E_{i\rightarrow j} \\
0 &\leq \Delta F_i \leq \Phi_{M_L} \\
E_{i\rightarrow j} &= \sum_k q_{i\rightarrow j}^k \\
0 &\leq q_{i\rightarrow j}^k \leq \bar{q}_{i\rightarrow j}^k
\end{align*}
\]

where

- \( \Delta F_i \) the increment of flow on the critical branch \( l \)
- \( \Phi_{M_L} \) the physical margin of the branch \( l \)
- \( E_{i\rightarrow j} \) is the D-1 total allocated quantity on \( i \rightarrow j \)
- \( q_{i\rightarrow j}^k \) the requested capacity on \( i \rightarrow j \) in bid \( k \)

The last step consists on a reformulation of the optimization problem with a constant second member.

In order to have a simpler illustration, the reformulation will be made on a simpler problem:

Let the contract paths be \( 1 \rightarrow 2 \) & \( 2 \rightarrow 1 \)

The bids are

\[
\begin{align*}
0 &\leq q_{1\rightarrow 2} \leq \bar{q}_{1\rightarrow 2} \\
0 &\leq q_{2\rightarrow 1} \leq \bar{q}_{2\rightarrow 1}
\end{align*}
\]

The flow on the only critical branch can be expressed as

\[
\Delta F = \alpha E_{1\rightarrow 2} + \beta E_{2\rightarrow 1}
\]

The relation between the exchanges and the bids gives:

\[
\begin{align*}
E_{1\rightarrow 2} &= q_{1\rightarrow 2} \\
E_{2\rightarrow 1} &= q_{2\rightarrow 1}
\end{align*}
\]

The problem is a linear problem which can be rewrite in the form \( y = Ax \)

\[
\begin{bmatrix}
\Delta F \\
E_{1\rightarrow 2} \\
E_{2\rightarrow 1}
\end{bmatrix} =
\begin{bmatrix}
\alpha & \beta & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
E_{1\rightarrow 2} \\
q_{1\rightarrow 2} \\
q_{2\rightarrow 1}
\end{bmatrix}
\]

Equation 4-5

Then, by expressing the equation 4-5 with a constant second member, the equation 4-6 is obtained.

\[
\begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
-1 & \alpha & \beta & 0 & 0 \\
0 & -1 & 0 & 1 & 0 \\
0 & 0 & -1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\Delta F \\
E_{1\rightarrow 2} \\
E_{2\rightarrow 1} \\
q_{1\rightarrow 2} \\
q_{2\rightarrow 1}
\end{bmatrix}
\]

with

\[
\begin{bmatrix}
\Delta F \\
E_{1\rightarrow 2} \\
E_{2\rightarrow 1} \\
q_{1\rightarrow 2} \\
q_{2\rightarrow 1}
\end{bmatrix} \leq
\begin{bmatrix}
\Phi_{M_L} \\
\infty \\
-\infty \\
-\bar{q}_{1\rightarrow 2} \\
-\bar{q}_{2\rightarrow 1}
\end{bmatrix}
\]

Equation 4-6

Finally the problem could be rewritten as shown in equation 4-7

53
\[ 0 = Ax \quad \text{with} \quad x = \begin{bmatrix} \Delta F_i \\ \vdots \\ E_{i\rightarrow j} \\ \vdots \\ q_{i\rightarrow j} \end{bmatrix} \quad \text{with the cost function} \quad \max \left( \sum_{k,(i,j)} p_{i\rightarrow j}^k \times q_{i\rightarrow j}^k \right) \quad \text{Equation 4-7} \]

### 4.1.2.2. Description of the two optimization tools

The optimization has been solved using two different tools in order to compare the quality of the results.

The first one, presented in figure 4-2, is a Scilab program which uses a simplex algorithm to solve the optimization problem. In order to use it a data file has to be computed, a program has been coded especially for that.

The exchanges and flows are obtained thanks to the solving of the optimization problem presented above. For the getting of the marginal prices the details are described in the appendix 4.

The second tool, presented in figure 4-2, is an optimizer written in C language by RTE and it uses a simplex algorithm to solve the optimization problem. In order to compute the optimization a data file has to be set up, a program has been coded especially for that.
The optimization problem which is solved here is the same as previously.

### 4.1.2.3. Optimization results

The optimization has been performed for two different lists of bids. The results presented in table 4-2 are satisfactory. The first thing which can be noticed is that the market values are very similar. This is a good hint that the allocated capacities are consistent. This conclusion is confirmed by the detailed comparison of the allocated capacities: for a proposed price different from zero, the same bids have been chosen and practically the same quantities have been allocated.

<table>
<thead>
<tr>
<th>Bids 1 (€)</th>
<th>Bids 2 (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Opt. 1</strong></td>
<td><strong>Opt. 2</strong></td>
</tr>
<tr>
<td>24203,7</td>
<td>24230,0</td>
</tr>
</tbody>
</table>

Table 4-2: Market value

The second part of the comparison concerns the computed exchanges and is illustrated by table 4-3:

<table>
<thead>
<tr>
<th>Exch.</th>
<th>Bids 1</th>
<th>Bids 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Opt. 1</strong></td>
<td><strong>Opt. 2</strong></td>
</tr>
<tr>
<td>A_B</td>
<td>895</td>
<td>895</td>
</tr>
<tr>
<td>B_A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B_C</td>
<td>615</td>
<td>615</td>
</tr>
<tr>
<td>C_B</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C_D</td>
<td>4609</td>
<td>4619</td>
</tr>
<tr>
<td>D_C</td>
<td>705</td>
<td>705</td>
</tr>
<tr>
<td>D_A</td>
<td>5326</td>
<td>1595</td>
</tr>
<tr>
<td>A_D</td>
<td>562</td>
<td>562</td>
</tr>
</tbody>
</table>

Table 4-3: Exchanges in MW

As illustrated in the table 4-3, a big difference appears concerning the exchange D-A. Indeed this is due to a difference of results concerning the bids with a price equal to zero. The Scilab optimizer allocates null quantities for the bids which have a price equal to zero, and the other optimizer a quantity different from zero. These two solutions are a correct optimization of the cost function. In a real auction, market rules would mention explicitly the treatment of zero-price bids, if they are permitted. Therefore, it is not a surprise that the comparison shows a point which will need to be discussed before the real application of the Flow-based method.

Concerning the values of the exchanges, the results are consistent with the results expected in reality.

This difference between the total allocated quantities has of course an impact on the associated flows which are not totally similar for the two optimizers.
The values of the marginal prices for the exchange D-A confirms the explanations given above concerning the divergences of this exchange.

<table>
<thead>
<tr>
<th>Exch.</th>
<th>Bids 1</th>
<th>Bids 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_B</td>
<td>0.93</td>
<td>0.51</td>
</tr>
<tr>
<td>B_A</td>
<td>0.44</td>
<td>0.26</td>
</tr>
<tr>
<td>B_C</td>
<td>1.61</td>
<td>0.89</td>
</tr>
<tr>
<td>C_B</td>
<td>1.31</td>
<td>0.77</td>
</tr>
<tr>
<td>C_D</td>
<td>2.63</td>
<td>1.55</td>
</tr>
<tr>
<td>D_C</td>
<td>0.75</td>
<td>0.42</td>
</tr>
<tr>
<td>D_A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A_D</td>
<td>2.52</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 4-4 : Marginal prices in €/MW

It can be verified that the marginal price correspond to the price from which the bids are accepted. For instance for the exchange A_B the marginal price is 0.93 €/MWh, as can be seen in the table 4-5.

<table>
<thead>
<tr>
<th>Price</th>
<th>Capa.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.21</td>
<td>0</td>
</tr>
<tr>
<td>0.26</td>
<td>0</td>
</tr>
<tr>
<td>0.51</td>
<td>0</td>
</tr>
<tr>
<td><strong>0.93</strong></td>
<td><strong>25</strong></td>
</tr>
<tr>
<td>1.08</td>
<td>85</td>
</tr>
<tr>
<td>1.46</td>
<td>50</td>
</tr>
<tr>
<td>1.5</td>
<td>15</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>4.83</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 4-5 : Allocated capacities

### 4.1.3. Global analysis of the study

This study was very interesting because it is the good illustration of the coordination which will be needed with the flow-based method.

The first notification which could be made is that coordination implies a common working way, which means:

- A common format of data. Indeed the given data were not totally similar (not the same degree of description for instance). It is very important to be efficient in the treatment of the data to provide a file which has the same organization, the same description of the data.

- In the same way a common tool of optimization will enable the actors to have a result with the same accuracy. Thus a next step of the collaboration could be to elaborate a common program for the data treatment (generation of the PTDF and the reference flows).
More generally the results obtained after the optimization seems to be consistent with the reality. But this study is insufficient. Indeed it is important to evaluate the behavior of the results at several dates. For instance, it could be interesting to make some periodic simulations with real data in order to detect some inconsistent results and try to evaluate the limit of the method.

4.2. **Feasibility test of the flow-based method and comparison with ATC approach**

The first goal of this study is to verify the reliability of the flow-based method. A reasonable approach seems to test the limit cases. Then we will add one more case in which the ATC conditions are imitated.

In order to have a progressive approach, the study is cut up in two sub-studies:
- An intra-day study where the calculation of capacity is made for a given day D and a given hour.
- A day-ahead study

Five different areas are considered A, B, C, D and E as shown in the figure 4-4. The simulation focuses on the zone A and the congestion rent between zone A and the neighboring countries. The goal is to maximize A's export. That is why the orientation of the exchanges will be from A to another area.

![Figure 4-4: Description of the simulation](image)

4.2.1. **Intra-day study**

4.2.1.1. **Parameters of the intra-day study:**

In order to compute the simulation, some parameters need to be gathered

- **Reference Exchanges**

Knowing that the base case corresponds to the intra-day situation, the reference exchanges are equal to the exchange in the base case.
Here is described the transfer PTDF matrix. Indeed as written in the theoretical part, it is easier to work with transfer PTDF than with zonal PTDF. Four critical branches are described in this study:

- 2 in the N context
- 1 in an N-1 context (with one fault on a line)
- 1 in an N-4 context (with four lines disconnected)

The computation of the PTDFs could be described as follows:

1. A load flow on the reference case gives the flow on the critical branch concerned.
2. Then an increase of 100MW is applied on the exchange concerned.
3. A new load flow enables us to have the flow on the critical branch after the exchange’s increase.
4. Knowing the linear equation \( \Delta F = PTDF \times \Delta E \), it is easy to compute the PTDF:

\[
PTDF = \frac{F_{\text{Exch +100MW}} - F_0}{100}
\]

<table>
<thead>
<tr>
<th></th>
<th>( A=&gt;B )</th>
<th>( A=&gt;C )</th>
<th>( A=&gt;D )</th>
<th>( A=&gt;E )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N A1-A2</td>
<td>6%</td>
<td>9%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>N A2-A3</td>
<td>6%</td>
<td>9%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>N-4 A1-A5</td>
<td>5%</td>
<td>8%</td>
<td>10%</td>
<td>19%</td>
</tr>
<tr>
<td>N-1 A6-B1</td>
<td>35%</td>
<td>15%</td>
<td>10%</td>
<td>6%</td>
</tr>
</tbody>
</table>

Table 4-7 : PTDF

**Notification**: The flow considered for the PTDF calculation must be in MW. Knowing that the flow will be given in Ampere, a conversion will be required in order to respect the homogeneity.

**Flow**

As for the reference exchange, the reference flows are the flow given by the base case. The physical margin is obtained by doing the difference between the maximal flow and the reference flow.

\[
\Phi_M = F_{\text{Max}} - F_{\text{Ref}}
\]

<table>
<thead>
<tr>
<th></th>
<th>Base case (MW)</th>
<th>Ref. exchanges (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A=&gt;B )</td>
<td>2191</td>
<td>2191</td>
</tr>
<tr>
<td>( A=&gt;C )</td>
<td>855</td>
<td>855</td>
</tr>
<tr>
<td>( A=&gt;D )</td>
<td>2416</td>
<td>2416</td>
</tr>
<tr>
<td>( A=&gt;E )</td>
<td>2656</td>
<td>2656</td>
</tr>
</tbody>
</table>

Table 4-6: Reference exchanges

**Table 4-8: physical margins**
4.2.1.2. Simulations

After the determination of the parameters, the simulations can be computed. The first group of simulations corresponds to several tests of reliability, like for instance trying to maximize the exchange in only one direction. Then an other test have been computed and corresponds to a maximization of the export for the zone A, and finally the last test illustrates the method based on ATC as calculated by the responsible of the area A.

In order to illustrate the different steps of the calculation two cases will be described:
- Maximization of the export
- Calculation based on ATC

Maximization of the export

The optimization problem is expressed as follows:

\[
\Delta F = \text{Matrix}_{\text{PTDF}} \Delta E \quad \text{Equation 4-9}
\]

\[
0 \leq \Delta F \leq \Phi_M \quad \text{Equation 4-10}
\]

\[
\max \left( \sum_{i} \text{Exch}_i \right) \quad \text{with } i \in \{ \text{A=>B, A=>C, A=>D, A=>E} \} \quad \text{Equation 4-11}
\]

This optimization problem is easily solved thanks to the solver of Microsoft Excel.

<table>
<thead>
<tr>
<th></th>
<th>phy. Marg. util. (A)</th>
<th>phy. Marg. max. (A)</th>
<th>Fcalc (A)</th>
<th>Fmax (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N A1-A2</td>
<td>200</td>
<td>707</td>
<td>2313</td>
<td>2820</td>
</tr>
<tr>
<td>N A2-A3</td>
<td>200</td>
<td>748</td>
<td>2252</td>
<td>2800</td>
</tr>
<tr>
<td>N-4 A1-A5</td>
<td>167</td>
<td>167</td>
<td>1904</td>
<td>1904</td>
</tr>
<tr>
<td>N-1 A6-B1</td>
<td>1169</td>
<td>2046</td>
<td>2003</td>
<td>2880</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ref. exchanges (MW)</th>
<th>Allocation (MW)</th>
<th>Final exchanges (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>2191</td>
<td>2338</td>
<td>4529</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>855</td>
<td>0</td>
<td>855</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>2416</td>
<td>0</td>
<td>2416</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>2656</td>
<td>0</td>
<td>2656</td>
</tr>
<tr>
<td>total</td>
<td>8118</td>
<td>2338</td>
<td>10456</td>
</tr>
</tbody>
</table>

Table 4-9: Results of the maximization of the export

As we can see the only exchange which increases is the exchange A=>B. This result of the optimization is totally consistent with the situation after allocation. Indeed the line which is in constraint after the optimization is the line A1-A5.

A brief analysis of the PTDF corresponding to the line shows us that the smaller PTDF is the one of the exchange A=>B. Knowing that this line was limited the optimization has privileged the exchange which has the smaller impact on the aggravation of the limitation.

The last step of the analysis is to verify that the solution belongs to the security domain. In order to do that a security analysis has been made thanks to the internal software of RTE to see if the solution was feasible. This security analysis consists on a succession of AC load flows and security tests. For instance if a fault appears on a line the new repartition of the flows on the network must be realizable or if some constraints occur, efficient remedial actions can be taken (for instance change of topology).
Here the analysis of security gives positive results. The system could support the list of predefined possible incidents.

- **Maximal export towards Area A, B, C, or D**

  The only thing which dissents from the previous case is the objective function. For an area \(i\), \(i \in \{B, C, D, E\}\) the optimization function is \(\max_{i} \{\text{Exch}_{A=>i}\}\).

- **Method based on ATC as calculated in the area A**

  Here the formulation of the optimization problem is a little bit different:

  The problem in a meshed network is that the exchanges are dependent on each other. The choice of the optimal ATC set is quite impossible to realize, because it implies to predict the choice of the other actors.

  Thus in order to have a not so bad repartition of the ATC, without doing too complex prediction about the choice of the other, the TSO of the zone A has decided to treat everyone in the same way. That why the physical margin is dispatch in an equitable way.

  This means in practical terms:

  We have four exchanges, thus the physical margin for each constraint calculated in the optimization problem is divided in four equal parts.

<table>
<thead>
<tr>
<th></th>
<th>phy. marg. util. (A)</th>
<th>phy. marg. max. (A)</th>
<th>Fcalc. (A)</th>
<th>Fmax (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N A1-A2</td>
<td>174</td>
<td>707</td>
<td>2287</td>
<td>2820</td>
</tr>
<tr>
<td>N A2-A3</td>
<td>174</td>
<td>748</td>
<td>2226</td>
<td>2800</td>
</tr>
<tr>
<td>N-4 A1-A5</td>
<td>167</td>
<td>167</td>
<td>1904</td>
<td>1904</td>
</tr>
<tr>
<td>N-1 A6-B1</td>
<td>425</td>
<td>2046</td>
<td>1259</td>
<td>2880</td>
</tr>
</tbody>
</table>

**Table 4-10: Results with the method based on ATC**

These results, presented in table 4-10, have been validated by comparing them with the result of the software used by the operational team to calculate the allocation. Additionally a security analysis ensures the feasibility of these allocations.
### 4.2.1.3. Results

<table>
<thead>
<tr>
<th>Allocation</th>
<th>ATC</th>
<th>Max export</th>
<th>Max A=&gt;B</th>
<th>Max A=&gt;C</th>
<th>Max A=&gt;D</th>
<th>Max A=&gt;E</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>585</td>
<td>2338</td>
<td>2338</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>365</td>
<td>0</td>
<td>0</td>
<td>1461</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>292</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1169</td>
<td>0</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>154</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>615</td>
</tr>
<tr>
<td>Total</td>
<td>1396</td>
<td>2338</td>
<td>2338</td>
<td>1461</td>
<td>1169</td>
<td>615</td>
</tr>
<tr>
<td>A=&gt;B</td>
<td>2776</td>
<td>4529</td>
<td>4529</td>
<td>2191</td>
<td>2191</td>
<td>2191</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>1220</td>
<td>855</td>
<td>855</td>
<td>2316</td>
<td>855</td>
<td>855</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>2708</td>
<td>2416</td>
<td>2416</td>
<td>2416</td>
<td>3585</td>
<td>2416</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>2810</td>
<td>2656</td>
<td>2656</td>
<td>2656</td>
<td>2656</td>
<td>3271</td>
</tr>
<tr>
<td>Total</td>
<td>9514</td>
<td>10456</td>
<td>10456</td>
<td>9579</td>
<td>9287</td>
<td>8733</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
</tr>
</thead>
</table>

Table 4-11: Summary of all the results

All the results obtained in table 4-11 show reasonable values. The security tests are positive for all the simulations. Even when we privilege only one direction, the result are consistent and ensure the security of the network.

### 4.2.2. Day-ahead study

#### 4.2.2.1. Parameters

- **Reference Exchanges**

  The available data do not exactly correspond to the studied situation. The simulation will focus on day-ahead allocation and the data are the one corresponding to the intra-day situation. Thus it is necessary to adapt the exchanges so that they correspond only to the yearly and monthly nominations.

  As the target day is identical to the base case day, this can be done simply by withdrawing from the total exchanges the volume of nominated capacities coming from the day-ahead and the intra-day allocation processes of that very day. Graphically this modification corresponds to a translation of our base case by considering the change of exchanges, as described the figure 4-5. In this figure the blue lines represent the constraints. Then the base case is translated to a fictive point which represents the target case.
\[ E_{\text{ref}} = \text{Nom}_{\text{Yearly target day}} + \text{Nom}_{\text{Monthly target day}} \] 

**Equation 4-12**

<table>
<thead>
<tr>
<th>basecase</th>
<th>Nom. DA+ID</th>
<th>Ref. exch=Nom Y+M</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>2191</td>
<td>343</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>855</td>
<td>269</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>2416</td>
<td>0</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>2656</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 4-12: Reference exchanges**

- **PTDF**

Any change for the PTDF compared to the intra-day study.

<table>
<thead>
<tr>
<th></th>
<th>FR=&gt;BE</th>
<th>FR=&gt;DE</th>
<th>FR=&gt;CH</th>
<th>FR=&gt;IT</th>
</tr>
</thead>
<tbody>
<tr>
<td>N A1-A2</td>
<td>6%</td>
<td>9%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>N A2-A3</td>
<td>6%</td>
<td>9%</td>
<td>11%</td>
<td>14%</td>
</tr>
<tr>
<td>N-4 A1-A5</td>
<td>5%</td>
<td>8%</td>
<td>10%</td>
<td>19%</td>
</tr>
<tr>
<td>N-1 A6-B1</td>
<td>35%</td>
<td>15%</td>
<td>10%</td>
<td>6%</td>
</tr>
</tbody>
</table>

**Table 4-13: PTDF**

- **Flow**

Here we need to calculate the \( F_{\text{ref}} \) after the applying of our modification of exchange. The change of reference flows are linearly linked with the change of exchange thanks to the transfer PTDF matrix. Thus it is easy to compute the new reference flow, as shown in the equations 4-13 and 4-14.
\[ \Delta F_{\text{Ref}} = M_{PTDF} \Delta E \] \hspace{1cm} \text{Equation 4-13}

where \( M_{PTDF} \) is the transfer PTDF matrix and \( \Delta E \) the decrease in exchange.

Then,

\[ F_{\text{Ref}} = F_{\text{Base Case}} - \Delta F_{\text{Ref}} \] \hspace{1cm} \text{Equation 4-14}

As in the previous calculation the physical margin is equal to \( \Phi_M = F_{\text{max}} - F_{\text{Ref}} \)

<table>
<thead>
<tr>
<th></th>
<th>( F_{\text{basecase}} ) (A)</th>
<th>( \text{DeltaF}_{\text{Ref}} ) (A)</th>
<th>( F_{\text{Ref}} ) (A)</th>
<th>( F_{\text{max}} ) (A)</th>
<th>( \text{Marge phy.} ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N A1-A2</td>
<td>2113</td>
<td>64</td>
<td>2049</td>
<td>2820</td>
<td>771</td>
</tr>
<tr>
<td>N A2-A3</td>
<td>2052</td>
<td>64</td>
<td>1988</td>
<td>2800</td>
<td>812</td>
</tr>
<tr>
<td>N-4 A1-A5</td>
<td>1737</td>
<td>55</td>
<td>1682</td>
<td>1904</td>
<td>222</td>
</tr>
<tr>
<td>N-1 A6-B1</td>
<td>834</td>
<td>229</td>
<td>605</td>
<td>2880</td>
<td>2275</td>
</tr>
</tbody>
</table>

Table 4-14: physical margins

- **List of bids**

The list of bids is given in a separated file. This file includes for each exchange:
  - The number which identifies the bid
  - The requested contract path (from area X to area Y)
  - The expected capacity
  - The proposed price

4.2.2.2. Simulations

In this part of the study, the simulations are the same as in the previous part and in addition a simulation using the flow-based method is computed.

Here the data includes the bids list. The optimization problem is similar to the one which has been described with the equations 4-9, 4-10 and 4-11. In order to simulate the situation of maximal export in one area, the only thing to do is to retain only bids for that contract path. After that the function to maximize is equivalent to the previous one.

The simulations are computed using the Scilab optimizer, which gives directly the marginal price, the market value and the congestion income as shown in table 4-15.
4.2.2.3. Results

<table>
<thead>
<tr>
<th></th>
<th>ATC Max export</th>
<th>Max FR=&gt;BE</th>
<th>Max FR=&gt;DE</th>
<th>Max FR=&gt;CH</th>
<th>Max FR=&gt;IT</th>
<th>Flow-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>J-1 A=&gt;B</td>
<td>777 3111</td>
<td>3111</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>J-1 A=&gt;C</td>
<td>486 0</td>
<td>0</td>
<td>1945</td>
<td>0</td>
<td>0</td>
<td>385</td>
</tr>
<tr>
<td>J-1 A=&gt;D</td>
<td>389 0</td>
<td>0</td>
<td>0</td>
<td>1556</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>J-1 A=&gt;E</td>
<td>204 0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>819</td>
<td>464</td>
</tr>
<tr>
<td>Total</td>
<td>1856 3111</td>
<td>3111</td>
<td>1945</td>
<td>1556</td>
<td>819</td>
<td>1581</td>
</tr>
<tr>
<td>A=&gt;B</td>
<td>2625 4959</td>
<td>4959</td>
<td>1848</td>
<td>1848</td>
<td>1848</td>
<td>2580</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>1072 586</td>
<td>586</td>
<td>2531</td>
<td>586</td>
<td>586</td>
<td>971</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>2805 2416</td>
<td>2416</td>
<td>2416</td>
<td>3972</td>
<td>2416</td>
<td>2416</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>2860 2656</td>
<td>2656</td>
<td>2656</td>
<td>2656</td>
<td>3475</td>
<td>3120</td>
</tr>
<tr>
<td>Total</td>
<td>9362 10617</td>
<td>10617</td>
<td>9451</td>
<td>9062</td>
<td>8325</td>
<td>9087</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
<th>Controllable constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>8,01 €</td>
<td>0,00 €</td>
<td>0,00 €</td>
<td>n.a.</td>
<td>n.a.</td>
<td>9,62 €</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>14,42 €</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0,11 €</td>
<td>n.a.</td>
<td>15,40 €</td>
</tr>
<tr>
<td>A=&gt;D</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>A=&gt;E</td>
<td>60,50 €</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0,00 €</td>
<td>36,57 €</td>
</tr>
<tr>
<td>Market Value</td>
<td>49 841,00 €</td>
<td>27 525,00 €</td>
<td>27 525,00 €</td>
<td>14 967,00 €</td>
<td>n.a.</td>
<td>30 378,00 €</td>
</tr>
<tr>
<td>Total outcome</td>
<td>25 576,14 €</td>
<td>0,00 €</td>
<td>0,00 €</td>
<td>213,95 €</td>
<td>n.a.</td>
<td>0,00 €</td>
</tr>
</tbody>
</table>

Table 4-15: Global results

The results are very satisfactory. For instance the results presenting for the ATC approach ensure the security of the network. Then the marginal prices and the market value are consistent with the price obtained in reality. As in the intra-day study all the simulations ensure the security of the network. The second important point is the comparison between the market values of the flow-based simulation and the one based on ATC. The first one is higher than the second one which means that the utilization of the flow-based method enables us to improve the solution as expected. Additionally the value of the marginal price and the exchanges are relatively consistent with the one obtained in reality.
In this part the aim is to compute the flow-based parameters for a big number of dates in order to analyze the parameters, and to observe their behavior in the time and for instance periodic behavior.

5.1. **Joining of the DACF files**

5.1.1. **Programs and data used**

- **DACF files**
  
  For this part of the study the Day-Ahead Congestion Forecasted files have been used. The data contained in each file allow load flow and three phase short circuit studies and describe the interconnected extra high voltage network. Appendix 1 contains all the explanations about how to use these files.

  The data base used contains all the DACF files which have been saved for each country and for the 4 following times: 03:30, 10:30, 12:30, and 19:30.

  In order to have a reasonable number of data some choices have been made:
  - The study has been limited to the time 10:30.
  - A time period has been chosen and represents one year and a half, between 01/01/2005 and 30/06/2006.

- **Computer program**
  
  For this part two programs are available, which have been developed by RTE before the beginning of the study. They enable on one hand to do the “DACF joining” and on the other hand to do a preliminary analysis before the “DACF joining” in order to detect the errors. Indeed the DACF files contain some incoherencies which makes a direct joining impossible.

  The first program, called *CountryAna*, has been used for a pre-analysis of the data to detect the majority of the errors, which correspond to incoherent data as described in table 5-3. Thanks to it a text-file is obtained with all the errors contained in the data files during one month.

  The procedure of collecting and filtering is described in the figure 5-1.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>Final text file for one month</td>
</tr>
<tr>
<td>Month</td>
<td>1. filter for selecting the time 10:30</td>
</tr>
<tr>
<td>Output file name</td>
<td>2. filter for ignoring warning and non pertinent error</td>
</tr>
</tbody>
</table>

**Text file for the times containing warning errors during one month**

*Figure 5-1: Data filtering*
The second program, called *CountryRec* has six different functions which are dedicated to both the joining and the analysis of the DACF files, but here the time scale is the day. The utilization of the different functions could be described as follows.

1. **Choosing the internal variables:**

   There are two internal variables which will add or not some constraints to the joining:
   - The first one is called “AllJoined”:
     
     | If the variable is equal to | Then                                      |
     |-----------------------------|--------------------------------------------|
     | TRUE                        | Even if there is an error the joining continues |
     | FALSE                       | If there is an error the joining is stopped |
   - The second one is called “MissingCountry”:
     
     | If the variable is equal to | Then                                      |
     |-----------------------------|--------------------------------------------|
     | TRUE                        | If a country is missing the joining is stopped |
     | FALSE                       | A missing country is not a fatal error     |

2. **Applying one of the functions:**

   The program has two main functions with different options concerning the date which can be described as shown in the table 5-1.

<table>
<thead>
<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANA</td>
<td>Today Analyses the joining for the current day</td>
</tr>
<tr>
<td></td>
<td>D Analyses the joining for the specified day</td>
</tr>
<tr>
<td></td>
<td>DH Analyses the joining for the specified day and the specified hour</td>
</tr>
<tr>
<td>REC</td>
<td>Today Try to join the files for the current day</td>
</tr>
<tr>
<td></td>
<td>D Try to join the files for the specified day</td>
</tr>
<tr>
<td></td>
<td>DH Try to join the files for the specified day and the specified hour</td>
</tr>
</tbody>
</table>

   **Table 5-1: Program functions**

5.1.2. **Choice of countries**

   It is not necessary to do the joining on all the DACF files. The larger the number of data more difficult is the joining and larger is the number of errors which need to be corrected. Therefore if the number of countries is too big the joining has less chance to be successful. Additionally it is important to keep in mind that the time period is one year and a half, which is why the number of data must not be too big in order to be efficient, and not to lose too much time with this part of the study.

   The countries which have been selected are represented in figure 5-2.
They are classified in two categories:

1. **The main countries**

   These countries have to be present in the joining, because they have a big impact on the network. Thus accurate topology and nodal injection are essential. If one of those countries is missing the joining is impossible.

   *France, Germany, Italy, Belgium, Netherlands, Switzerland*

2. **The optional countries**

   These countries are less important than the previous ones. An accurate set of exchanges is sufficient, it will be obtained later. If one of those countries is missing we can add a so-called reference file, a file chosen to replace the missing one.

   *Poland, Czech republic, Slovenia, Spain, Austria*

   The reference directory has been built by considering a division in two main categories which are constituted of two subcategories.

   The first distinction is between the winter and the summer month and the other one between the weekend and the rest of the week.

   In the table 5-2 is described the original files used to create the reference files. For instance the Spanish file dated from the 18/01/2005 has been used as reference Spanish file for the winter and week period. This means that if the Spanish file is missing for a day of a week in winter, the reference file described above will be used.
5.1.3. Practical approach

After the description of all the data used and parameters chosen, the global description of the joining can be established, as it is described in the figure 5-3. After the first analysis of the data, the next step is the establishment of the error list. Then it is easy to classify the different kinds of errors and to write the associated program of the correction. Finally the last step consists to implement the program for real error and to join the files.

![Figure 5-3: Joining process](image-url)
**Description of the main steps:**

1. Listing of the recurrent errors and creation of the program of correction:

   By analyzing the list of all the errors a list of type of errors has been established. These lists contained the most recurrent typing errors.

   In table 5-3 all the corrected errors and their corrections can be found.

<table>
<thead>
<tr>
<th>Error</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Country</strong></td>
<td></td>
</tr>
<tr>
<td>An optional country is missing</td>
<td>The corresponding reference file is added</td>
</tr>
<tr>
<td>The UCTE name of the country is not correct</td>
<td>Changing the name for the good one</td>
</tr>
<tr>
<td><strong>Nodes</strong></td>
<td></td>
</tr>
<tr>
<td>The node appears more than one time with different characteristics</td>
<td>Saving the node with the biggest active power generation</td>
</tr>
<tr>
<td>The node appears more than one time with the same characteristics</td>
<td>Saving the first one and erasing the others</td>
</tr>
<tr>
<td>The name of the node is not written with the ISO code</td>
<td>Change the name for the good one</td>
</tr>
<tr>
<td><strong>Lines</strong></td>
<td></td>
</tr>
<tr>
<td>The line appears more than one time with the same characteristics</td>
<td>Saving the first one and erasing the others</td>
</tr>
<tr>
<td><strong>Lines with an Xnode</strong></td>
<td></td>
</tr>
<tr>
<td>An Xnode is connected with more than one line</td>
<td>Selected the good one and erasing the other</td>
</tr>
<tr>
<td><strong>2 windings transformers</strong></td>
<td></td>
</tr>
<tr>
<td>The order of the transformer is wrong. The transformer seems to be defined more than one time.</td>
<td>Checking the values of the nominal Powers and changing the values of the orders as a consequence</td>
</tr>
<tr>
<td><strong>2 windings transformers regulation</strong></td>
<td></td>
</tr>
<tr>
<td>The order of the transformer is wrong. The transformer seems to be defined more than one time.</td>
<td>Changing the order by checking the position in the list</td>
</tr>
<tr>
<td><strong>2 windings transformers regulation</strong></td>
<td></td>
</tr>
<tr>
<td>The number of plots (N) and the number (n) of the used plot is not coherent: N&lt; n</td>
<td>Finding the more accurate values and modified the number or/and the used plot</td>
</tr>
<tr>
<td><strong>Xnode</strong></td>
<td></td>
</tr>
<tr>
<td>The status of the border line is not coherent (not the same for the two concerned countries)</td>
<td>Choosing one status as the good one and change the other.</td>
</tr>
</tbody>
</table>

The second step after the gathering of those errors was to create a program which could correct automatically these typing errors. The language which has been chosen to write this program is Python.

The program so created contains around ten corrections which have to be applied to each specific error in the executive part of the program. This implementation corresponds to the next step.

2. **Correction of the specific errors.**

   For the majority of the errors the correction needs an accurate corrected value. This implies that the correction has to be preceded by a manual research in the validate files to find the most accurate value.

   Around one hundred and fifty errors has been corrected thank to the list of errors.
It is important to keep in mind that at this time the totality of the error has not been corrected. Indeed one error could hide another one. The remaining errors have been corrected directly during the joining part.

It is also important to notice that some isolated errors have been corrected manually in order to save some time.

5.1.4. **Result and possible improvements**

The results can be summarized in the table 5-4.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total number of dates</strong></td>
<td>546</td>
</tr>
<tr>
<td>Number of joined files in 2005</td>
<td>248</td>
</tr>
<tr>
<td>Number of joined files in 2006</td>
<td>181</td>
</tr>
<tr>
<td><strong>Total number of joined files</strong></td>
<td>387</td>
</tr>
<tr>
<td>Total number of non-joined files</td>
<td>161</td>
</tr>
</tbody>
</table>

Table 5-4: Joining results

This result is very satisfactory. Indeed the number of joined files seems to be sufficient for the following of the study. The time repartition of the data is very good. Except for February and March 2005 there is no big lack of data. It is very important to be able to do the future study on all the periods of the years.

5.2. **Modification of topology**

The changes taken into consideration here are the apparition (which means the launching of a new line) and disappearing of a line.

In order to detect these changes in the line’s topology several methods have been implemented and tested in order to elaborate the most accurate method of determination.

5.2.1. **First approach: the basic one**

This method is based on a simple principle: gather the date of apparition and disappearing of the line to detect the change of topology, where
- the date of apparition is viewed as the first date of presence of the line during the studied period
- the date of disappearing is viewed as the last date of presence of the line during the studied period.

To simplify the implementation and the analysis of the results, the implementation of this method has been made only on the border lines. A program has been implemented and gives as output the results shown in table 5-5.
Between the 01/01/2005 and the 06/30/2006

BE

<table>
<thead>
<tr>
<th>Line</th>
<th>Node</th>
<th>From Date</th>
<th>To Date</th>
<th>Files</th>
</tr>
</thead>
<tbody>
<tr>
<td>BACHEN11</td>
<td>XAC_LO11</td>
<td>27/04/2005</td>
<td>29/06/2006</td>
<td>359</td>
</tr>
<tr>
<td>BACHEN12</td>
<td>XAC_LO11</td>
<td>01/01/2005</td>
<td>19/06/2005</td>
<td>101</td>
</tr>
<tr>
<td>BAUBAN21</td>
<td>XAU_MO21</td>
<td>20/04/2005</td>
<td>21/06/2006</td>
<td>14</td>
</tr>
<tr>
<td>BAUBAN22</td>
<td>XAU_MO21</td>
<td>01/01/2005</td>
<td>29/06/2006</td>
<td>446</td>
</tr>
<tr>
<td>BAVLGM12</td>
<td>XAV_AV11</td>
<td>01/01/2005</td>
<td>24/02/2005</td>
<td>45</td>
</tr>
<tr>
<td>BBELVA21</td>
<td>XBE_OX21</td>
<td>01/01/2005</td>
<td>29/06/2006</td>
<td>460</td>
</tr>
<tr>
<td>BCESCH21</td>
<td>XCE_SC21</td>
<td>01/01/2005</td>
<td>29/06/2006</td>
<td>460</td>
</tr>
<tr>
<td>BHERD+1R</td>
<td>XLI_MB11</td>
<td>19/04/2005</td>
<td>29/06/2006</td>
<td>419</td>
</tr>
<tr>
<td>BAVLGM11</td>
<td>BAVLGM11</td>
<td>11/10/2005</td>
<td>29/03/2006</td>
<td>6</td>
</tr>
<tr>
<td>XAV_AV11</td>
<td>BAVLGM12</td>
<td>19/04/2005</td>
<td>12/06/2006</td>
<td>319</td>
</tr>
<tr>
<td>XAV_AV11</td>
<td>BAVLGM13</td>
<td>04/04/2006</td>
<td>29/06/2006</td>
<td>75</td>
</tr>
<tr>
<td>XAV_MA11</td>
<td>BAVLGM11</td>
<td>27/11/2005</td>
<td>12/06/2006</td>
<td>114</td>
</tr>
<tr>
<td>XAV_MA11</td>
<td>BAVLGM12</td>
<td>11/10/2005</td>
<td>29/06/2006</td>
<td>125</td>
</tr>
<tr>
<td>XAV_MA11</td>
<td>BAVLGM13</td>
<td>24/04/2006</td>
<td>01/06/2006</td>
<td>4</td>
</tr>
<tr>
<td>XJA_CH21</td>
<td>BJAMIO2</td>
<td>01/01/2005</td>
<td>24/02/2005</td>
<td>45</td>
</tr>
<tr>
<td>XJA_CH21</td>
<td>BJAMIO2R</td>
<td>19/04/2005</td>
<td>29/06/2006</td>
<td>418</td>
</tr>
<tr>
<td>XLI_MB11</td>
<td>BHERD+1</td>
<td>01/01/2005</td>
<td>24/02/2005</td>
<td>45</td>
</tr>
<tr>
<td>XME_MB11</td>
<td>BMEERH1</td>
<td>01/01/2005</td>
<td>24/02/2005</td>
<td>45</td>
</tr>
<tr>
<td>XME_MB11</td>
<td>BMEERH11</td>
<td>19/04/2005</td>
<td>29/06/2006</td>
<td>409</td>
</tr>
<tr>
<td>XZA_BS11</td>
<td>BZANDV12</td>
<td>01/01/2005</td>
<td>29/06/2006</td>
<td>444</td>
</tr>
<tr>
<td>XZA_GT11</td>
<td>BZANDV12</td>
<td>01/01/2005</td>
<td>29/06/2006</td>
<td>452</td>
</tr>
</tbody>
</table>

Table 5-5: Results of the determination of new branches with the simple method

In the table 5-5 we can see the results obtained for the interconnections concerning Belgium. The two first columns represent the name of the line considered. In the third column we can see the date of apparition of the line and in the fourth column the date of disappearing of the line and finally in the last column the number of files where the line where represented. Unfortunately the results shown in the table 5-5 are not very satisfactory, because it is quasi impossible to utilize them. Indeed a lot of problems could be underlined:

- It is not possible to make the difference between maintenance on a line at the beginning (respectively at the end) of the studied period and an apparition (respectively disappearing) of a new line.

- A change in the name of the line will be seen as an apparition of a new line (for the new syntax) and a disappearing (for the old syntax).

- For the case where there is a group of lines which goes from or/and to a group of nodes, the line could be used alternatively. In the resulting table these kinds of lines appears separately while they have to be considered as a group.

In conclusion these method is not exploitable in particular in the case where all the lines (internal and borderlines) are considered. That is why another approach has been considered.
5.2.2. Second approach: Utilization of the “current limit”

5.2.2.1. Method of determination

The first idea is to reduce the number of data in order to be able to apply the method on all
the branches and not only the border lines. That is why the variable which are considered here are
the composite branches and not the simple one. A composite branch is defined here as the
aggregation of all the branches which exist between two substations.

The second main idea is to find a characteristic value which can be an indicator. Indeed it
would be more accurate to consider a constant which would change if a branch appeared or
disappeared. The characteristic value which has been chosen is the current limit, because it is a
characteristic of the line and as a consequence it is fixed for a given line.

In order to obtain the current limit corresponding to the composite branch, the value
considered here is the sum of all the current limits of the simple branches which belong to the
composite branch studied.

\[
\text{CompositeBranch} = \{ B_{r_1}, B_{r_2}, ..., B_{r_N} \}
\]

\[
\text{Max \_ CurrentLimit} = \sum_{\{ B_{r_1}, B_{r_2}, ..., B_{r_N} \}} \text{CurrentLimit}_{B_i}
\]

Equation 5-1: composite branches and current limit

According to these considerations, if a new branch appears or an old one disappears, then
the maximum of the current limit must increase or decrease.

The major problems of this method rest on the following assumptions:

- All the TSOs have correctly filled in the DACF files.
- The amount of joining files is insufficient to see the change of current limit (there is no too long
  period during which the current limit is missing).

Study limited to one country, France

In spite of the problems described previously the first results seem to be satisfactory. This
study has been limited to France in order to study a small number of data. First a program was
created to save the current limit of each composite branch during the time period considered (i.e.
01/01/2005 to 30/06/2006). Then to present the results in a more illustrative way, the graphs of the
temporal current limit evolution have been drawn.

The first notification which can be made is the huge number of results. Indeed for France
xxx graphs have been obtained. In the case where all the countries would be represented a manual
study of each graph would be very time consuming.

However the graphs are not all different. By dismissing the isolated changes of the current
limit and by projecting the values of the missing current limit, the following notifications can be
made:

- A big part of the graphs seems to be periodic.
- These periodic graphs can be classified in three types, as shown below.
By considering these characteristics, it seems legitimate to interpret the results as follows:

- If the pattern of the first six months of the year 2005 is identical to the pattern of the six first months of the year 2006 (i.e. in the periodic case), then the maximum of current limit has not been modified and as a consequence the topology is still the same.
- In the opposite case, the maximum of the current limit has been modified and the topology has been modified.

According to these new conclusions the number of data can be reduced, by adding a new step before the analyzing of the graphs:

1. Calculating the difference between the existing data corresponding to the six first months of the year 2005 and the existing data corresponding to the six first months of the year 2006 and then calculating the mean value of the current limit. If the mean is inferior in absolute value to an accurate threshold then the corresponding case would be the periodic one.

2. As a consequence, the only graphs which need to be studied are the ones which disregard the criteria.
5.3. **Determination of the critical lines**

A critical branch represents a line of the network which could probably limit the commercial exchanges between the areas because it reaches often its physical limits.

A basic interpretation of this definition could be to say that a branch is critical if its flows often reach or over-cross a determined limit (here it is the current limit) or a value close to this limit (like for example 70% of this value).

Thus the first step has been to save all the transit values for each branch between 01/01/2005 and 30/06/2006. The best approach was to use the DACF data gathering during the joining part and to compute a load flow in order to obtain the transit. That is why a program dedicated to this task has been developed by RTE. This program executes a load flow by considering the approximation of the direct current. It utilizes as input a joined DACF files and gives as output a table with the name, the transit and the current limit values for each date. The validation of the program (the results are consistent) is detailed in Appendix 3.

![Figure 5-5: Transit achievement](image)

**Conclusion**

Unfortunately this part of the test has been stopped before the end of the internship. Indeed this approach was very experimental and the method did not ensure us the obtaining of results. Additionally the time to obtain results was very short. In that context it was more pertinent to focus on a simple case to have a first view of the situation. This simple approach is described in the next paragraph.

5.4. **Simple approach: a model limited to the interconnections**

5.4.1. **Hypothesis and method**

In order to verify the consistency of the data used, a first calculation of PTDF has been made, according to the following hypothesis:

- The participating nodes are chosen manually, which means according to our own judgment but by following some basic rules:
The chosen nodes are not too close to the interconnection in order to obtain realistic and homogeneous values of the PTDF.

The chosen nodes are spread in the space in order to see the variation in all the country and not only in one part.

According to the size of the country and the importance of the country the number of nodes considered varies.

In the table 5-6 the repartition of the nodes and their UCTE names are given.

<table>
<thead>
<tr>
<th>BE</th>
<th>Gramme</th>
<th>BRAMM1</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>Dieren</td>
<td>NDIM-A1</td>
</tr>
<tr>
<td>DE</td>
<td>Dödenen</td>
<td>D7OPLA1</td>
</tr>
<tr>
<td></td>
<td>Dollern</td>
<td>L2 DOLL1</td>
</tr>
<tr>
<td></td>
<td>Regen</td>
<td>D8RAG_1</td>
</tr>
<tr>
<td></td>
<td>Oberseck</td>
<td>D2OBA_1</td>
</tr>
<tr>
<td></td>
<td>Pulveringen</td>
<td>D4PULV1</td>
</tr>
<tr>
<td>CH</td>
<td>Chamossaire</td>
<td>SCHAMO1</td>
</tr>
<tr>
<td></td>
<td>Sils</td>
<td>SSILS 1</td>
</tr>
<tr>
<td></td>
<td>Gröden</td>
<td>SGÖSGL1</td>
</tr>
<tr>
<td>IT</td>
<td>Baggio</td>
<td>IBAGM11</td>
</tr>
<tr>
<td></td>
<td>Venezia</td>
<td>IVZV11</td>
</tr>
<tr>
<td></td>
<td>Lago</td>
<td>ILAIN11</td>
</tr>
<tr>
<td>CZ</td>
<td>Chodov</td>
<td>CCHD_1</td>
</tr>
<tr>
<td></td>
<td>Prosenice</td>
<td>CPRN 1</td>
</tr>
<tr>
<td>AT</td>
<td>Linz</td>
<td>OLIENZ1</td>
</tr>
<tr>
<td></td>
<td>Dunnrohr</td>
<td>ODUERN1</td>
</tr>
<tr>
<td></td>
<td>Hessenberg</td>
<td>OHEISE1</td>
</tr>
<tr>
<td>SI</td>
<td>Bencno</td>
<td>LFRIC1</td>
</tr>
<tr>
<td>ES</td>
<td>Trillo</td>
<td>ETRILL1</td>
</tr>
<tr>
<td>PL</td>
<td>Plock</td>
<td>ZPLO141</td>
</tr>
<tr>
<td>FR</td>
<td>Sani</td>
<td>FSSV 01</td>
</tr>
<tr>
<td></td>
<td>Vevey</td>
<td>FVERFE1</td>
</tr>
<tr>
<td></td>
<td>Barnabos</td>
<td>FBAR NA1</td>
</tr>
</tbody>
</table>

Table 5-6 : Participating nodes

- The critical branches are limited to the interconnections.

Recall: The results have been computed for a period of one year and a half.

5.4.2. PTDF Results:

The first idea is to analyze the global behavior of the PTDF. With this aim in view, a sample of results has been chosen then the average and the deviation has been computed, as shown in the table 5-7:

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT_CH, BGRAMM1</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>AT_CH, SSILS1</td>
<td>-0.1564</td>
<td>0.0234</td>
</tr>
<tr>
<td>AT_CH, ETRILL1</td>
<td>-0.0366</td>
<td>0.0064</td>
</tr>
<tr>
<td>AT_CZ, D4PULV1</td>
<td>0.0243</td>
<td>0.0039</td>
</tr>
<tr>
<td>BE_FR, D4PULV1</td>
<td>-0.9661</td>
<td>0.0472</td>
</tr>
<tr>
<td>BE_FR, ODUERN1</td>
<td>-0.4351</td>
<td>0.0186</td>
</tr>
<tr>
<td>DE_FR, D8RAG_1</td>
<td>0.4592</td>
<td>0.0328</td>
</tr>
<tr>
<td>DE_FR, ETRILL1</td>
<td>-0.1038</td>
<td>0.0182</td>
</tr>
</tbody>
</table>

Table 5-7 : Average and Deviation for PTDF
By analyzing the means, the following notification could be made:

- The PTDF “AT_CH, BGRAMM1” has for participating node the hub BGRAMM1 that is why it is PTDF is equal to zero.
- The closer the critical branch is to the hub, the bigger the PTDF is. That is why the PTDF of the branch BE_FR are bigger than the ones of the branch AT_CZ.
- The closer the participating node is to the critical branch, the bigger the PTDF is.

As illustrated in the figures 5-7 and 5-8, the behavior of the deviation is closely connected to the behavior of the average PTDF.

Detailed analyze:

As expected the PTDFs are very sensitive to the change of topology of the network. This sensitivity does not make easy the analysis of the individual graphs. Indeed the graphs show isolated points and are not really constant. Without knowing exactly which modification has been made on the network it is impossible to interpret with precision the graphs.

Although some possible interpretation about the behavior could be made:
For instance let consider the curve of repartition of the PTDF for “AT_CH, CPRN__1”:

- For this case it is possible to distinguish two levels in the curve the change of the average value in March 2006 shows that a change of topology has appeared.
- There is also an isolated point with a value which is not explicable, maybe a bad set of entry data for this date.
There is a bigger variation of the data during the summer. Maybe it is due to the fact that there is more maintenance of the lines during the summer (this assumption is a generalization of an observation made for France).

With the analysis of the graphs the only solid conclusion is that the PTDFs are very sensitive to the changes of topology.

5.5. Conclusion

Concerning the quality of data, it is important to notice that there are mistakes in the given UCTE data. These mistakes introduce a deviation of the situation that we want to simulate and the simulation which is actually simulated.

Another problem of this study has been to determine the parameters for all the countries. Indeed the choice of the critical branches and the participating nodes is peculiar to each participant and depends on internal consideration that another person cannot assume. Additionally it has been shown that the nodal PTDF were very sensitive to the topology and today it is impossible to know all the changes of topology which have been made in the past.

In a second time the other point which has slowed down the study is the fact that the IT program has been elaborated during the study and thus the new functions had to be tested during the study. Sometime it was difficult to know if the mistakes came from the data or the program. Maybe it would be more efficient to work in several steps:
- Add all the necessary functions and test the IT program on one good set of data.
- Then to do the study on a shorter period 1 month
- If it is possible to work on a larger set of data

In spite of this cutting of the work, the problem of the determination of the external parameters will persist. A first idea for reducing the impact of this determination could be to determine only one set of PTDF and participating nodes and to use it for all the study. Furthermore it could be interesting to determine in collaboration with the other European participants this set of critical branches and participating nodes and from this set of parameters make the study on a short period.
6.1. Summary

This master thesis aimed to analyze a new method of capacity allocation, the method flow-based.

First this master thesis could be considered as a support to understand the flow-based method. Indeed the first aim of this thesis has been to describe the flow-based method and to give in the report all the keys for the reader to have a good understanding of the method.

The second aim of this master thesis has been to compute several simulations to prove the feasibility of the flow-based method and the better results obtained compared to those obtained with the current method based on ATC. Moreover these simulations have also enabled us to show the important issues of the future studies concerning method.

The first simulation is an illustration of the applying of the flow-based method between several actors. It shows the necessity of a coordinated work. Moreover the results presented for these simulations were good and consistent with the reality. Thus the flow-based method had a good behavior for this simulation.

The second simulation illustrates the feasibility of the flow-based method and the obtaining of better results compared to the current method based on ATC. It is a very important point which proves the interest of the flow-based method. Indeed as we know the flow-based method has a lower dependence to the parameters, and enables the actors not to do the kind of hypotheses which are made with the method based on ATC. The improvement of the results is positive argument for the applying of the flow-based method.

Finally the last simulation illustrates the beginning of determination of flow-based parameters based on old data with all the problems that this determination implies. In spite of the partial results obtained this simulation has shown a major issue of the applying of the flow-based method, the fact that flow-based method needs a strong coordination between the actors.

6.2. Future works

The simulations have shown the necessity of a coordinated work between the actors. Thus the first thing to do is to work on the common calculation tool which will enable the actors to do easily their calculations and will ensure the quality and homogeneity of the results. An important issue during the elaboration of this tool will be to verify the accuracy of a DC load flow. Indeed if the results of the DC load flow are too far of the reality, we need to implement a tool which uses a normal load flow. This would imply an increase of the difficulties for the implementation of the
tool and maybe an increase of the time of computation. Thus the choice of the load flow approach is an important issue for the development of the tools.

According to the fact that it is very difficult to do the simulations on old data, it could be interesting to do some coordinated simulations in real time. It would enable the actors to have accurate results, and could also enable them to improve the process of computation of the method.

In a second time after this other coordinated simulations and the determination of some set of parameters it would be interesting to come back to the simulations of the chapter fifth to test the different topologies of the network with the critical branches and the participating nodes defined previously. The first step would be to improve the gathering part and to elaborate a more complex program in order to correct automatically all the errors of the input file. Then the second step would be to analyze the PTDF and for instance to observe the behavior of the PTDF with changes of the reference data.

As we can see there is still a lot to do. This master thesis was just a little contribution to the project which will continue to evaluate the flow-based method and to make its applying possible.
As explained in the chapter three, the Power Distribution factor is the influence on the flow on a critical branch of every additional MW injected at a participating node.

- **N context**, which means normal context without fault:

![Diagram showing calculation of the PTDF in an N context](image)

Figure A-1: Calculation of the PTDF in a N context

The expression of the nodal PTDF $\alpha_{j \rightarrow k}^j$ is the influence of the injection of 1 MW at node $i$ on the branch $j \rightarrow k$.

Let $F_{j \rightarrow k}^{\text{Ref}}$ be the flow of the branch $j \rightarrow k$ in the reference state.

Let $F_{j \rightarrow k}'$ be the flow of the branch $j \rightarrow k$ after the injection of 1 MW at node $i$ (and drainage at the hub).

$$\alpha_{j \rightarrow k}^j = \frac{F_{j \rightarrow k}' - F_{j \rightarrow k}^{\text{Ref}}}{1} \quad \text{Equation A-1}$$

- **N-1 context**: 

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It is also possible to express the nodal PTDF as a function of nodal PTDF in the N context, as developed in the appendix 1:

Let $\alpha_{jk,i}$ be the PTDF of the line $j \rightarrow k$ after the disconnection of the line $p \rightarrow q$

$$\alpha_{jk,i} = \alpha_{jk,i} + \alpha_{pq,i} \times \frac{\alpha_{jk,p} - \alpha_{jk,q}}{1 - (\alpha_{pq,p} - \alpha_{pq,q})} \text{ if } jk \neq pq$$

$$\tilde{\alpha}_{pq,i} = 0$$

Equations A-2

Knowing that the N state is equivalent to the following N-1 state (all the flows are equal except the flow on the branch $p \rightarrow q$):

N state

N-1 State

Figure A-2: Calculation of PTDF in a N-1 context

Figure A-3: Description of the N-1 state
The equivalent N-1 state considered in figure A-3 could be expressed as the superposition of three states, as shown in figure A-4:

![Figure A-4: Division in three states](image)

Thanks to this superposition it is easy to find a new expression of $\alpha_{jk,i}$ as described in Figure A-5:

![Figure A-5: Relation between the three states and the PTDFs.](image)

$$\alpha_{jk,i} = 1 \times \tilde{\alpha}_{jk,i} + \alpha_{pq,i} \times \tilde{\alpha}_{jk,q} + \left(-\alpha_{pq,i}\right) \times \tilde{\alpha}_{jk,p}$$

This means:

$$\alpha_{jk,i} = \tilde{\alpha}_{jk,i} + \alpha_{pq,i} \times \left(\tilde{\alpha}_{jk,q} - \tilde{\alpha}_{jk,p}\right) \quad \text{Equation A-3}$$

The previous relation is valid for all $i$. 

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Thus, particularly for i=p and i=q:

\[ \alpha_{jk,p} = \tilde{\alpha}_{jk,p} + \alpha_{pq,p} \times \left( \tilde{\alpha}_{jk,q} - \tilde{\alpha}_{jk,p} \right) \]  
Equation A-4

\[ \alpha_{jk,q} = \tilde{\alpha}_{jk,q} + \alpha_{pq,q} \times \left( \tilde{\alpha}_{jk,q} - \tilde{\alpha}_{jk,p} \right) \]

Then:

\[ \alpha_{jk,p} - \alpha_{jk,q} = \left( \tilde{\alpha}_{jk,p} - \tilde{\alpha}_{jk,q} \right) \times \left[ 1 - \left( \alpha_{pq,q} - \alpha_{pq,p} \right) \right] \]  
Equation A-5

Finally thanks to the substitution of \( \tilde{\alpha}_{jk,p} - \tilde{\alpha}_{jk,q} \) we get the equation A-6.

\[ \tilde{\alpha}_{jk,i} = \alpha_{jk,i} + \alpha_{pq,i} \frac{\alpha_{jk,p} - \alpha_{jk,q}}{1 - \left( \alpha_{pq,q} - \alpha_{pq,p} \right)} \]  
Equation A-6
Appendix B: UCTE format

As explained in [11], this appendix describes the UCTE format adopted for data exchange and provides all the necessary instructions about its use. The data refer to load flow and three phase short circuit studies and describe the interconnected extra high voltage network.

The following blocks are defined:
- COMMENTS (C)
- NODE (N)
- LINES (L)
- 2 WINDINGS TRANSFORMERS (T)
- 2 WINDINGS TRANSFORMERS REGULATION (R)

Each block is introduced by a key line consisting of the two characters “##” and of the character given above in brackets. The end of a block is given by the next key line or the end of the file. No “end command” is to be used. The sequence of the blocks in the file is recommended as above. The information of the above defined blocks is written in lines and the contents are separated by a blank. This blank (empty space) has to be respected strictly.

The comment block “##C” at the top of data should describe at least the provider of the file and the reference point of the data. Additional comment blocks introduced by “##C” and containing comment lines may be given at any place of the file.

Each description of a regulated 2 windings transformer (##T) needs a description of a 2 windings transformer regulation (##R). Three winding transformers, which are described with help of three independent two winding transformers can have the regulation on only one of them.

Format version identification

Inside the file it is necessary to have an identification of the used format version in order to ensure an automatic processing of the data. The key line of the comment block “##C” is extended with a supplementary information as follows:

##C YYYY.MM.DD

The date is the format version identification and has to be identical to the last date given in the title page (coming into force: YYYY.MM.DD).

For the format used before 01.09.2003 no date is to be given in the key line of the comment block (only ##C).

File name convention

The file name convention is:

<yyyyymmddd>_ <HHMM>_ <TY><w>_<cc><v>.uct with

    yyyyymdd: year, month and day,
    HHMM: hour and minute,
    TY: File type; FO = Forecast, SN = Snapshot, RE = Reference, LR = Long Term Reference
    w: day of the week, starting with 1 for Monday,
    cc: the ISO country-code for national datasets, “UC” for UCTE-wide merged datasets without X nodes and “UX” for UCTE-wide merged datasets with X nodes,
    v: version number starting with 0.
A node code structure

Within the “NODES” block “##N”, key lines consisting of the three characters „##Z” and the ISO country identification (2 characters) must be introduced. Those key lines assign all following nodes to that country (e.g. ##ZAT for Austria).

The following 8-character alphanumeric code is used for identifying network nodes unequivocally.

1st character: UCTE country code
2nd-6th character: short description of the geographical spot
7th character: voltage level
8th character: letter or figure for differentiating bus bars (optional)

It is recommended to choose an appropriate node name and to keep it for all the UCTE data exchanges.

X-nodes on tie lines

Fictitious nodes are located at the electric middle of each tie line. The defined X-nodes are binding for all users. Here are described all the X-nodes connecting the UCTE control blocks/areas. The Appendix 2 has its own version number because the X-nodes change more often and have to be updated independently of the UCTE format.

UCTE country codes

<table>
<thead>
<tr>
<th>#</th>
<th>country code</th>
<th>name (1st character of the node)</th>
<th>ISO code (to be used in the ##N section for ##Z and in the ##E section)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Österreich (Austria)</td>
<td>O</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>Belgique (Belgium)</td>
<td>B</td>
</tr>
<tr>
<td>7</td>
<td>CH</td>
<td>Schweiz (Switzerland)</td>
<td>S</td>
</tr>
<tr>
<td>8</td>
<td>CZ</td>
<td>Ceska Republika (Czech Republic)</td>
<td>C</td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>Deutschland (Germany)</td>
<td>D</td>
</tr>
<tr>
<td>11</td>
<td>E</td>
<td>Espana (Spain)</td>
<td>E</td>
</tr>
<tr>
<td>12</td>
<td>F</td>
<td>France (France)</td>
<td>F</td>
</tr>
<tr>
<td>17</td>
<td>I</td>
<td>Italia (Italy)</td>
<td>I</td>
</tr>
<tr>
<td>24</td>
<td>NL</td>
<td>Nederland (Netherlands)</td>
<td>N</td>
</tr>
<tr>
<td>26</td>
<td>PL</td>
<td>Polska (Poland)</td>
<td>Z</td>
</tr>
<tr>
<td>31</td>
<td>SLO</td>
<td>Slovenija (Slovenia)</td>
<td>L</td>
</tr>
<tr>
<td>35</td>
<td>--</td>
<td>Fictitious border node</td>
<td>X</td>
</tr>
</tbody>
</table>

Table B-2: Country code nodes
## N (NODES)

<table>
<thead>
<tr>
<th>columns</th>
<th>type</th>
<th>length</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>character</td>
<td>8</td>
<td>Node (code)</td>
</tr>
<tr>
<td>9</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10-21</td>
<td>character</td>
<td>12</td>
<td>Node (geographical name)</td>
</tr>
<tr>
<td>22</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>integer</td>
<td>1</td>
<td>Status: 0 = real, 1 = equivalent</td>
</tr>
<tr>
<td>24</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>integer</td>
<td>1</td>
<td>Node type code (0 = P and Q constant (PQ node); 1 = Q and ( U ) constant, 2 = P and U constant (PU node), 3 = U and ( \theta ) constant (global slack node, only one in the whole network))</td>
</tr>
<tr>
<td>26</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>27-32</td>
<td>real</td>
<td>6</td>
<td>Voltage (reference value) (kV)</td>
</tr>
<tr>
<td>33</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>34-40</td>
<td>real</td>
<td>7</td>
<td>Active load (MW)</td>
</tr>
<tr>
<td>41</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>42-48</td>
<td>real</td>
<td>7</td>
<td>Reactive load (MVar)</td>
</tr>
<tr>
<td>49</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>50-56</td>
<td>real</td>
<td>7</td>
<td>Active power generation (MW)</td>
</tr>
<tr>
<td>57</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>58-64</td>
<td>real</td>
<td>7</td>
<td>Reactive power generation (MVar)</td>
</tr>
</tbody>
</table>

Table B-3: Description of the node name

## L (LINES)

<table>
<thead>
<tr>
<th>columns</th>
<th>type</th>
<th>length</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>character</td>
<td>8</td>
<td>Node 1 (code)</td>
</tr>
<tr>
<td>9</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10-17</td>
<td>character</td>
<td>8</td>
<td>Node 2 (code)</td>
</tr>
<tr>
<td>18</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>character</td>
<td>1</td>
<td>Order code (1, 2, 3 ... 9, A, B, C ... Z)</td>
</tr>
<tr>
<td>20</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>integer</td>
<td>1</td>
<td>Status (0, 1, 2 or 7, 8, 9) *</td>
</tr>
<tr>
<td>22</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>23-28</td>
<td>real</td>
<td>6</td>
<td>Resistance R (Ω)</td>
</tr>
<tr>
<td>29</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>30-35</td>
<td>real</td>
<td>6</td>
<td>Reactance X (Ω) **</td>
</tr>
<tr>
<td>36</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>37-44</td>
<td>real</td>
<td>8</td>
<td>Susceptance B (μS)</td>
</tr>
</tbody>
</table>
**Table B-4: Description of the line name**

*) real element in operation \((R, X)\) only positive values permitted)  
8: real element out of operation \((R, X)\) only positive values permitted)  
1: equivalent element in operation  
9: equivalent element out of operation  
2: busbar coupler in operation \((\text{definition: } R=0, X=0, B=0)\)  
7: busbar coupler out of operation \((\text{definition: } R=0, X=0, B=0)\)  

**) the absolute value of the reactance for lines has to be greater than or equal to 0.050 \(\Omega\) (to avoid division by values near to zero in load flow calculation)

***) in case of tie line the element name has to be the same as used in Appendix 2

**Remarks:**

1. All nodes of the “LINES” description must be defined in the “NODES” block indifferently whether the line is declared out of operation or not.

2. All lines must be defined in the “LINES” block, indifferently whether the line is declared out of operation or not. In the “LINES” block, the tie lines are to be given grouped together in a section.

###T (2 WINDINGS TRANSFORMERS)

<table>
<thead>
<tr>
<th>columns</th>
<th>type</th>
<th>length</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>character</td>
<td>8</td>
<td>Node 1 (code) (non-regulated winding)</td>
</tr>
<tr>
<td>9</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10-17</td>
<td>character</td>
<td>8</td>
<td>Node 2 (code) (regulated winding)</td>
</tr>
<tr>
<td>18</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>character</td>
<td>1</td>
<td>Order code ((1, 2, 3 \ldots 9, A,B,C \ldots Z))</td>
</tr>
<tr>
<td>20</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>integer</td>
<td>1</td>
<td>Status ((0, 1 \text{ or } 8, 9)) **</td>
</tr>
<tr>
<td>22</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>23-27</td>
<td>real</td>
<td>5</td>
<td>Rated voltage 1: non-regulated winding (kV)</td>
</tr>
<tr>
<td>28</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>29-33</td>
<td>real</td>
<td>5</td>
<td>Rated voltage 2: regulated winding (kV)</td>
</tr>
<tr>
<td>34</td>
<td>character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>35-39</td>
<td>real</td>
<td>5</td>
<td>Nominal power (MVA)</td>
</tr>
</tbody>
</table>

**Table B-5: Description of the transformers name**

*) pertaining to the rated voltage of the non-regulated winding 1 of the transformer

**) real element in operation \((R, X)\) only positive values permitted)  
8: real element out of operation \((R, X)\) only positive values permitted)
1: equivalent element in operation
9: equivalent element out of operation

***) the absolute value of the reactance for transformers has to be greater than or equal to 0.050 Ω (to avoid division by values near to zero in load flow calculation)

Remarks:
All nodes of the “TRANSFORMERS” description must be defined in the “NODES” block indifferently whether the transformer is declared out of operation or not.

##R (2 WINDINGS TRANSFORMERS REGULATION)

<table>
<thead>
<tr>
<th>columns</th>
<th>type</th>
<th>length</th>
<th>contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-8</td>
<td>Character</td>
<td>8</td>
<td>Node 1 (code) (non-regulated winding)</td>
</tr>
<tr>
<td>9</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10-17</td>
<td>Character</td>
<td>8</td>
<td>Node 2 (code) (regulated winding)</td>
</tr>
<tr>
<td>18</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Integer</td>
<td>1</td>
<td>Order code (1, 2, 3 ... 9, A,B,C ... Z)</td>
</tr>
<tr>
<td>20</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>21-25</td>
<td>Real</td>
<td>5</td>
<td>u (%)</td>
</tr>
<tr>
<td>26</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>27-28</td>
<td>Integer</td>
<td>2</td>
<td>n</td>
</tr>
<tr>
<td>29</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>30-32</td>
<td>Integer</td>
<td>3</td>
<td>n’</td>
</tr>
<tr>
<td>33</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>34-38</td>
<td>Real</td>
<td>5</td>
<td>U (kV) (optional)</td>
</tr>
<tr>
<td>39</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>40-44</td>
<td>Real</td>
<td>5</td>
<td>u (%)</td>
</tr>
<tr>
<td>45</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>46-50</td>
<td>Real</td>
<td>5</td>
<td>Θ (°)</td>
</tr>
<tr>
<td>51</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>52-53</td>
<td>Integer</td>
<td>2</td>
<td>n</td>
</tr>
<tr>
<td>54</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>55-57</td>
<td>Integer</td>
<td>3</td>
<td>n’</td>
</tr>
<tr>
<td>58</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>59-63</td>
<td>Real</td>
<td>5</td>
<td>P (MW) (optional)</td>
</tr>
<tr>
<td>64</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>65-68</td>
<td>Character</td>
<td>4</td>
<td>Type (ASYM: asymmetrical, SYMM: symmetrical)</td>
</tr>
<tr>
<td>69</td>
<td>Character</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table B-6: Description of the transformer regulation name

Remarks:
1. For each transformer, columns 1 to 19 have to be the same in the ##R card as in the ##T card.
2. n = number of taps, counted the following way: it is the difference between the intermediate position (neutral) and the positive or negative ultimate position (e.g. a transformer with total 27 taps (+13, neutral,-13) is given as n = 13 in the UCTE format).
Appendix C: Joining results

In the table C-1 is presented the global results of the joining of DACF files and listed all the joined files

<table>
<thead>
<tr>
<th>Total number of dates</th>
<th>546</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of joined files in 2005</td>
<td>248</td>
</tr>
<tr>
<td>Number of joined files in 2006</td>
<td>181</td>
</tr>
<tr>
<td>Total number of joined files</td>
<td>387</td>
</tr>
<tr>
<td>Total number of non-joined files</td>
<td>161</td>
</tr>
</tbody>
</table>

Table C-1: Global results of the joining part

In the tables C-2 and C-3 the list of all the files are presented. For each date it is possible to see if the joining has been successful are not. If there is a green V the joining has been successful, if there is a red X the joining has failed.

Table C-2: Detailed results for the year 2005
<table>
<thead>
<tr>
<th>Date</th>
<th>01/01/2006</th>
<th>01/02/2006</th>
<th>01/03/2006</th>
<th>01/04/2006</th>
<th>01/05/2006</th>
<th>01/06/2006</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
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<td>V</td>
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<tr>
<td></td>
<td>V</td>
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<td>V</td>
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<td>V</td>
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<td>V</td>
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<td></td>
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<td>V</td>
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<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>X</td>
<td>V</td>
<td></td>
<td>V</td>
<td>V</td>
</tr>
</tbody>
</table>

Table C-3: Detailed results for the year 2006
During the internship a computer program has been developed and has been used for several of the project:
- to gather the UCTE files
- to do load flow calculation
- to compute PTDF

Others internal RTE programs which have already been validated have also been used for the load flow calculation in order to ensure the quality of the results. However the problem with these old programs was the denomination of the data which was not the UCTE nomination. Thus the utilization of these programs implies the construction of a dictionary to convert the names of the elements of the network. That is why the creation of this new computer program was very important. In this context an aim of the internship has been to test this new computer program which has the advantage to work directly with UCTE data.

This appendix will first present the global principles of the calculation and then the results of some simple validations.

**Theoretical presentation**

**Load flow calculation**

For the load flow calculation the approximation of the direct current is applied. This means that the following hypotheses are taken into account:

- $V_i = V_n$ where $V_n$ is the corresponding nominal voltage
- $R=0$
- No losses
- The angles $\theta_i$ are small and thus $\sin(\theta) \approx \theta$

The voltage are constant, thus the objective is to evaluate the angles. The calculations are made by considering only the active power.

After applying the approximation, the expression of the active transmitted power becomes:

$$P_{ij} = \frac{V_{\text{base}}^2 (\theta_i - \theta_j + \alpha_k)}{X_{ij}}$$  
Equation D-1
where
\[
\begin{align*}
X_{ij} & \text{ is the reactance of the line between } i \text{ and } j \\
\theta_i & \text{ is the angle at the node } i \\
\theta_j & \text{ is the angle at the node } j \\
\alpha_k & \text{ is the phase shift of the possible phase shifter between } i \text{ and } j \\
(\alpha_k=0 \text{ if there is no phase shifter})
\end{align*}
\]

Then the active power at the node \(i\) could be expressed as:
\[
P_i = \sum_i P_j = \sum_i \frac{V^2}{X_{ij}} (\theta_i - \theta_j + \sigma_q - \sigma_p) \quad \text{Equation D-2}
\]

Where
\[
\begin{align*}
\sigma_q & \text{ is the origin angle of the possible phase shifter between } i \text{ and } j \\
\sigma_p & \text{ is the end angle of the possible phase shifter between } i \text{ and } j
\end{align*}
\]

Then the system which has to be solved is:
\[
P = J\theta \quad \text{Equation D-3}
\]

where
\[
\begin{align*}
P & \text{ is the vector of the active power} \\
\theta & \text{ is the vector of angles}
\end{align*}
\]

\[
\begin{align*}
J_{ii} & = \sum_{i=j} V^2 \\
J_{ij} & = -\frac{V^2}{X_{ij}}
\end{align*}
\]

**PTDF computation**

A nodal PTDF express the sensitivity of the injection at a node \(k\) on the flow of a line \(i \rightarrow j\) as already explained in chapter three and in appendix A.

For a node:
\[
PTDF_{ki}^{i \rightarrow j} = \frac{\Delta P_j}{\Delta P_k} \quad \text{where} \quad \left\{ \begin{array}{l}
P_j \text{ is the flow on the line } i \rightarrow j \\
P_k \text{ the injected power at node } k
\end{array} \right. \quad \text{Equation D-4}
\]

For a phase shifter:
\[
PTDF_{\alpha_k}^{i \rightarrow j} = \frac{\Delta P_j}{\Delta \alpha_k} \quad \text{where } \alpha_k \text{ is the phase shift} \quad \text{Equation D-5}
\]
Validation of the computer program

The validation of the computer program concerns the load flow calculation. The validation consists in a comparison between the computer program, another program and manual calculations. The network used here is a simple network with only 14 nodes.

The UCTE data are presented in the table D-1.

<table>
<thead>
<tr>
<th>node i</th>
<th>Vi</th>
<th>( \theta_i )</th>
<th>node j</th>
<th>Vj</th>
<th>( \theta_j )</th>
<th>Xij</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNOD0111</td>
<td>380</td>
<td>5,07</td>
<td>FNOD0211</td>
<td>380</td>
<td>0</td>
<td>4,2721</td>
</tr>
<tr>
<td>FNOD0111</td>
<td>380</td>
<td>5,07</td>
<td>FNOD0311</td>
<td>380</td>
<td>-7,94</td>
<td>14,293</td>
</tr>
<tr>
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<td>380</td>
<td>0</td>
<td>FNOD0511</td>
<td>380</td>
<td>-4,06</td>
<td>12,554</td>
</tr>
<tr>
<td>FNOD0311</td>
<td>380</td>
<td>-7,94</td>
<td>FNOD0411</td>
<td>380</td>
<td>-5,57</td>
<td>12,348</td>
</tr>
<tr>
<td>FNOD0411</td>
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<td>-5,57</td>
<td>FNOD0211</td>
<td>380</td>
<td>0</td>
<td>12,73</td>
</tr>
<tr>
<td>FNOD0621</td>
<td>220</td>
<td>-10,14</td>
<td>FNOD01121</td>
<td>220</td>
<td>-10,86</td>
<td>4,8134</td>
</tr>
<tr>
<td>FNOD0621</td>
<td>220</td>
<td>-10,14</td>
<td>FNOD1221</td>
<td>220</td>
<td>-11,24</td>
<td>6,1905</td>
</tr>
<tr>
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<td>220</td>
<td>-10,14</td>
<td>FNOD1321</td>
<td>220</td>
<td>-11,41</td>
<td>3,1526</td>
</tr>
<tr>
<td>FNOD0921</td>
<td>220</td>
<td>-10,87</td>
<td>FNOD0121</td>
<td>220</td>
<td>-11,17</td>
<td>2,0449</td>
</tr>
<tr>
<td>FNOD0921</td>
<td>220</td>
<td>-10,87</td>
<td>FNOD1421</td>
<td>220</td>
<td>-12,4</td>
<td>6,543</td>
</tr>
<tr>
<td>FNOD1021</td>
<td>220</td>
<td>-11,17</td>
<td>FNOD1121</td>
<td>220</td>
<td>-10,86</td>
<td>4,6481</td>
</tr>
<tr>
<td>FNOD1221</td>
<td>220</td>
<td>-11,24</td>
<td>FNOD1321</td>
<td>220</td>
<td>-11,41</td>
<td>4,8371</td>
</tr>
<tr>
<td>FNOD1321</td>
<td>220</td>
<td>-11,41</td>
<td>FNOD1421</td>
<td>220</td>
<td>-12,4</td>
<td>8,422</td>
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<td>FNOD0411</td>
<td>380</td>
<td>-5,57</td>
<td>FNOD0711</td>
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<td>15,098</td>
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<td>FNOD0411</td>
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<td>-5,57</td>
<td>FNOD0921</td>
<td>220</td>
<td>-10,87</td>
<td>40,156</td>
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<tr>
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<td>380</td>
<td>-4,06</td>
<td>FNOD0621</td>
<td>220</td>
<td>-10,14</td>
<td>18,195</td>
</tr>
<tr>
<td>FNOD0711</td>
<td>380</td>
<td>-9,04</td>
<td>FNOD0871</td>
<td>27</td>
<td>-9,04</td>
<td>12,718</td>
</tr>
<tr>
<td>FNOD0711</td>
<td>380</td>
<td>-9,04</td>
<td>FNOD0921</td>
<td>220</td>
<td>-10,87</td>
<td>7,9425</td>
</tr>
</tbody>
</table>

Table D-1: UCTE data

Then the transmitted power and the injected power have been manually calculated thanks to the equation D-1.

The table D-2 shows the coherence of the results regardless the method. The differences between the different results obtained are very small. Thus the results obtained with the new program are consistent.
Table D-2: comparison of the flows computed with the three methods

The last verification concerns the injections. The table D-3 shows that the formula $P = \sum_i P_i$ is verified:

<table>
<thead>
<tr>
<th>UCTE name</th>
<th>New Prog.</th>
<th>Other Prog.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNOD0111</td>
<td>4419,36</td>
<td>4420,3</td>
</tr>
<tr>
<td>FNOD0211</td>
<td>326,64</td>
<td>326,8</td>
</tr>
<tr>
<td>FNOD0311</td>
<td>-1884</td>
<td>-1880</td>
</tr>
<tr>
<td>FNOD0411</td>
<td>-956</td>
<td>-966,1</td>
</tr>
<tr>
<td>FNOD0511</td>
<td>-152</td>
<td>-147,1</td>
</tr>
<tr>
<td>FNOD0621</td>
<td>-224</td>
<td>-224</td>
</tr>
<tr>
<td>FNOD0711</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FNOD0871</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>FNOD0921</td>
<td>-590</td>
<td>-589,9</td>
</tr>
<tr>
<td>FNOD1021</td>
<td>-180</td>
<td>-180</td>
</tr>
<tr>
<td>FNOD1121</td>
<td>-70</td>
<td>-70</td>
</tr>
<tr>
<td>FNOD1221</td>
<td>-122</td>
<td>-122</td>
</tr>
<tr>
<td>FNOD1321</td>
<td>-270</td>
<td>-270</td>
</tr>
<tr>
<td>FNOD1421</td>
<td>-298</td>
<td>-298</td>
</tr>
</tbody>
</table>

Table D-3: comparison of the injections computed with the two programs

In conclusion the results concerning the load flow calculation give accurate results. Indeed if we compare the results obtained with the new program and the results obtained with the old one, they are very close to each other. Thus we can conclude that this part of the program could be validated.
As explained in [7], to have a representation of the intensity of a constraint, the quantity used is the shadow price.

In our context, the cross-border capacity allocation, the shadow price corresponds to the variation of the market value defined in equation 3-16 where the limit of the constraints is increased of 1 MW. The shadow price is homogeneous to a price.

To illustrate this, we can come back to the example developed in the theoretical part. By considering the case of the explicit auction, a recall of the set of bids used is drawn here:

<table>
<thead>
<tr>
<th>Contractual Path</th>
<th>Proposed Price</th>
<th>Requested quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A=&gt;B</td>
<td>22.00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>18.00 €</td>
<td>100 MW</td>
</tr>
<tr>
<td></td>
<td>14.00 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>26.50 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>24.50 €</td>
<td>100 MW</td>
</tr>
<tr>
<td></td>
<td>22.50 €</td>
<td>25 MW</td>
</tr>
<tr>
<td>A=&gt;C</td>
<td>2.00 €</td>
<td>50 MW</td>
</tr>
<tr>
<td></td>
<td>1.00 €</td>
<td>200 MW</td>
</tr>
<tr>
<td></td>
<td>0.50 €</td>
<td>50 MW</td>
</tr>
<tr>
<td>B=&gt;C</td>
<td>9.50 €</td>
<td>25 MW</td>
</tr>
<tr>
<td></td>
<td>7.50 €</td>
<td>100 MW</td>
</tr>
<tr>
<td></td>
<td>5.50 €</td>
<td>25 MW</td>
</tr>
</tbody>
</table>

Table E-1: Set of bids the example described in chapter 3

When the optimum is obtained, two critical branches are in constraints:
- $A_1 \rightarrow B_1$ in a N-1 context (fault on $A_4 \rightarrow C_7$) \((1)\)
- $B_4 \rightarrow C_2$ in a N-1 context (fault on $A_4 \rightarrow C_7$) \((2)\)

This means that at the optimum the variation of flow is equal to the physical margin. For the branch \((1)\), the physical margin is $\Phi_u = \Delta F = 50,8 MW$ and the theoretical market value (i.e. before applying the round to the lower MW of the allocated quantity) is 4066.03 €.

To evaluate the shadow price, it is necessary to compare the theoretical market value with the one when the physical margin is increased of 1 MW.

Thus for the branch \((1)\) when $\Phi_u = 51,8 MW (= 50,8 MW + 1 MW)$, the market value becomes 4112.86 € (this value is obtained thanks to a new optimization with the new value of the physical margin).

Finally the shadow price for the first constraint $A_1 \rightarrow B_1$ with N-1 $A_4 \rightarrow C_7$ is:

$$\frac{4112.86€ - 4066.03€}{1 MW} = 46.83€ / MW$$

With the same reasoning, the shadow price for the second branch $B_4 \rightarrow C_2$ with N-1 $A_4 \rightarrow C_7$ is:

$$32.78€ / MW$$
The last step is to establish the relation between the shadow prices and the marginal prices. This relation is obtained by using the correspondent PTDF:

\[ P_M^{i\rightarrow j} = \sum_{k \in C} PTDF_k^{i\rightarrow j} \times F_k \]  

Equation E-1

Where:

- \( P_M^{i\rightarrow j} \) is the marginal price for the exchange \( i \rightarrow j \)
- \( PTDF_k^{i\rightarrow j} \) is the PTDF of the critical branch \( k \) for the exchange \( i \rightarrow j \)
- \( F_k \) is the shadow price for the critical branch \( k \)

NB: the critical branches are those which are in constraint at the optimum

For instance, let calculate the marginal price for the exchange A\( \rightarrow \)B:

\[ PTDF_{Br1}^{A\rightarrow B} = 0.465 \]  
\[ PTDF_{Br2}^{A\rightarrow B} = 0.00 \]

Thus:

\[ P_M^{A\rightarrow B} = 0.465 \times 46.83 + 0.00 \times 32.78 = 21.77\text{€/MW} \]

The table E-2 gives all the marginal prices of the example.

<table>
<thead>
<tr>
<th>Sit.</th>
<th>Ouvr.</th>
<th>Shadow prices</th>
<th>A( \rightarrow )B</th>
<th>A( \rightarrow )C</th>
<th>B( \rightarrow )C</th>
<th>B( \rightarrow )A</th>
<th>C( \rightarrow )A</th>
<th>C( \rightarrow )B</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 A4-C7</td>
<td>A1( \rightarrow )B1</td>
<td>46.83 €/MM</td>
<td>PTDF</td>
<td>46.5%</td>
<td>30.5%</td>
<td>0.0%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>N1 A4-C7</td>
<td>B4( \rightarrow )C2</td>
<td>32.78 €/MM</td>
<td>PTDF x Sh.Pr.</td>
<td>21.77 €/MM</td>
<td>14.27 €/MM</td>
<td>0.00 €/MM</td>
<td>0.00 €/MM</td>
<td>7.50 €/MM</td>
</tr>
</tbody>
</table>

Table E-2: Marginal prices

Notification:

The netting ban is manifested in marginal prices which are positive or equal to zero.
In the case of market coupling the netting is allowed and the equation E-2 could be applied:

\[ P_M^{i\rightarrow j} = -P_M^{j\rightarrow i} \]  

Equation E-2
References


