LMP – based method for Identification of the homogeneous areas of the electric market

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Abstract

The creation of a unified European electric system, reliable and effective is one of the challenges of the European integration process.

From the technical point of view, the success of the interconnection and the harmonization of the electric systems of the European countries is undeniable.

However, the European electric market remains divided into several zones, disconnected (entirely or partially) in matter of electricity prices (SPOT, future, balancing market).

The comprehension of this phenomenon needs the analysis of fundamental drivers of the prices of electricity, and particularly by the study of the interaction between the transmission lines congestions and the power plants units commitment.

The Locational Marginal Price (LMP) criteria, associated to the probabilistic approach in the inter-connected electric system working simulation, seems well adapted to this kind of studies.

This paper focuses on the methodology used to identify the homogenous price zones on the European electric market. This approach is based on statistical clustering techniques of LMP.

A few examples are given.

Index Terms

Electricity market, Clustering, Market Areas, Locational Marginal Price, Congestions.

Background and aim

Today's European interconnected electricity system totals 15 national networks operated by 35 TSOs (Transmission System Operator).

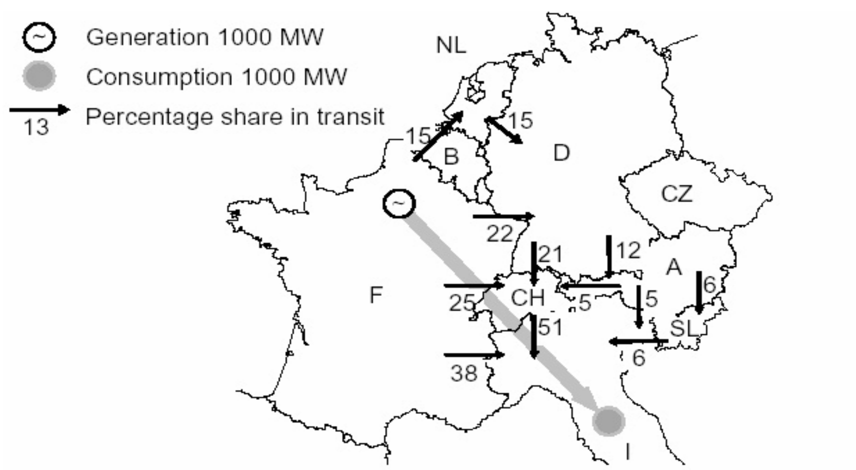
Initially, the interconnection of national electricity systems was designed to ensure their safe operation and in particular, to share and optimise the primary and secondary reserves required by safety standards.

From this point of view, there is no doubting the success of the interconnection and harmonization achieved by the European electricity systems.

The electricity system deregulation process and the liberalization of the European electricity market are resulting in strong growth of energy transits between national electricity transmission networks. In the last 30 years, the total volume of exchanges within the UCTE has increased by more than 500%, from approximately 50 TWh in 1975 to more than 260 TWh in 2003.

Accordingly, the problem of constraints in the transmission lines, and in particular interconnection lines, within the European electricity system are becoming increasingly acute.

It is noteworthy that a commercial energy transaction between two countries generates considerable physical flows throughout the lines of the interconnected systems. For instance, in the following, we represent the physical transits resulting from the supply of 1000 MW power from France to Italy.



Power flow distribution of a 1000-MW-transport from Northern France to Italy

Figure 1:

In practice, interconnection constraints are taken into consideration by the National TSO, which limit the commercial exchanges and the interfaces in question to guarantee the safety of the system.

Accordingly, the greater volume of transactions limited at a given interface by the TSO, the greater the deviation in the electricity price on both sides of this interface.

While the mechanisms to limit cross-border exchanges may vary from one interface to another (implicit or explicit auctions, pro-rata capacity allocation, aso), the borders segmenting the European electricity market in most cases use the historical borders of those countries. That is the case in France, in Italy (at the end of 2004), on the Iberian Peninsula, in Belgium, the Netherlands, Germany and Austria.

Today, almost all the main borders in Europe are subject to permanent or occasional congestion, rendering the electricity system fragile and causing a disparity or even a total disconnection between electricity prices on the various electricity markets in Europe.

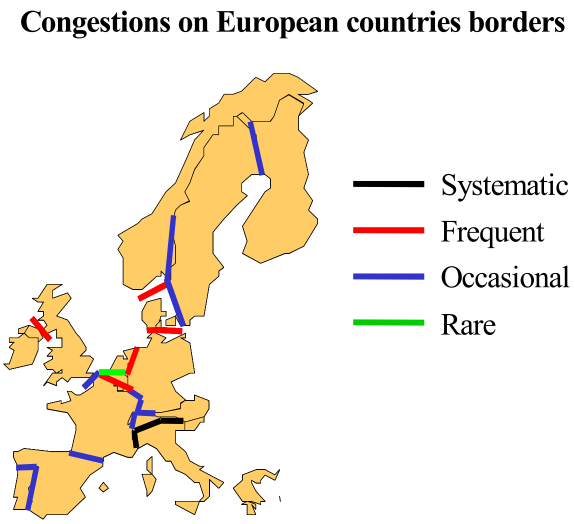


Figure 2:

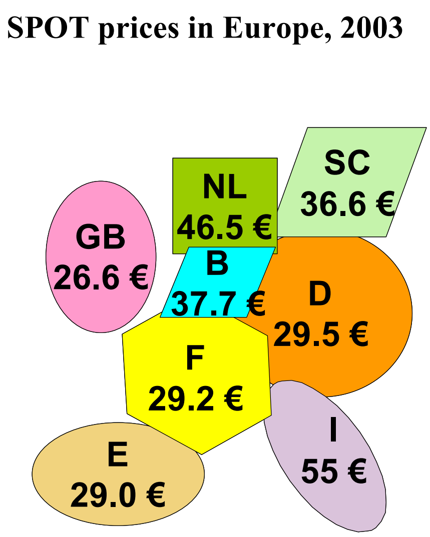


Figure 3

The research work currently being carried out within the EDF R&D division are designed to answer, among other things, the question of to what extent the current segmenting of the electricity market corresponds to the physical reality of the system's operation and what the segmenting would be if it were based on the physical realities of the current European electrical system, free from the historical and political aspects of the problem.

This work will make a contribution to the European thinking about the optimum concept of the unified electricity market in Europe, in line with the spirit of the European commission decisions.

Principle of the approach

Our approach involves an analysis of the fundamental cost of electricity and, more particularly, the interference between the technical parameters of the interconnected electricity system (network topology, characteristics of the demand, electricity transmission and generation assets, applicable safety rules etc) and the Locational Marginal Price.

The concept of the Locational Marginal Price (LMP) is used as a basic element for the operational management of electricity transmission networks by several TSO, most notably by one of the biggest North American electricity companies, PJM.

Here is the definition of the Locational Marginal Price as given by this company:

"Locational Marginal Price (LMP) is the least marginal cost of supplying the next increment of electric demand at a specific location (node) on the electric power network, taking into account both supply (generation / import) bids and demand (load / export) offers and the physical aspects of the transmission system including transmission and other operational constraints."

The sensitivity of Location Marginal Prices to network constraints on one side and to the unavailability of generating units on the other enables the TSO to use them as a pertinent guideline when managing producer access to a congested network, by establishing a link between the network physical capacities and the respective competitive positions of the various generation units.

Below we present a diagram illustrating the performance of the Locational Marginal Prices when there is a need for redispatching production due to a transit constraint affecting a line.

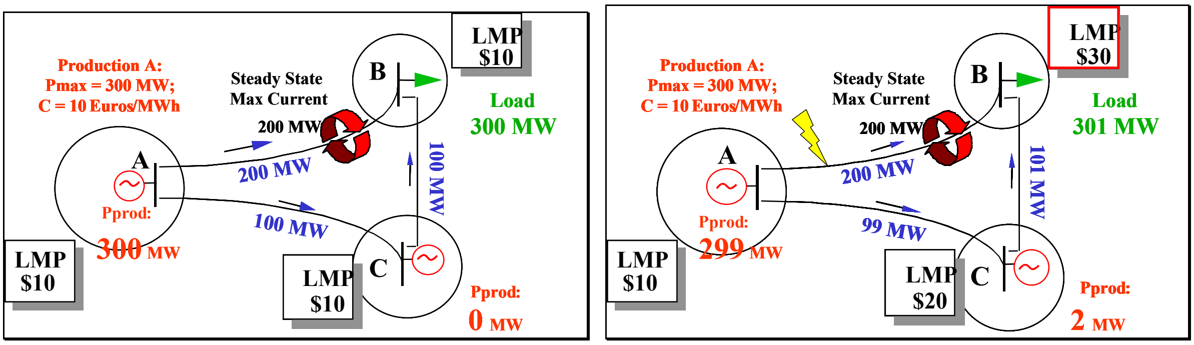


Figure 4.

The LMPs are a numerical translation of the influence of the network on the generation unit commitment. It is possible to identify zones containing nodes with similar LMPs, that is, affected identically by network constraints. These zones can be interpreted as perimeters within which producers are brought into direct competition.

To do this, a model of the European electricity system has been put through a number of simulations, subsequent to which the LMP values were analysed using statistical data analysis methods. In the following, we describe the model and the process of simulation with the results obtained.

Model of European electricity system

The model used in the study consists of:

- Transmission system,
- Generation units,
- Loads.

The transmission system is described with the conventional components: The substations, lines, transformers, phase shifters, back-to-back converters, DC links.

For the lines and transformers, the following properties are used in the calculations: resistance (R), reactance (X), admissible maximal intensity under normal conditions or during contingency analysis and the unforeseeable and programmed unavailability factors. The model takes into account the works for which the reference voltage is in excess of 200 kV.

The generation units are separated into 2 categories: thermal units and hydraulic units:

- Thermal units: For these groups, the maximum power (Pmax), the variable costs and the unforeseeable and programmed unavailability rates are given. Each unit is attached to the correct node of the transmission network.
- The hydraulic units: the description contains hydraulic generation (or pumping) target output at 0 cost and a maximum power indication. Additional turbining can be carried out with an associated extra cost.

Consumption. Consumption is modelled with loads attached to the correct nodes of the transmission network.

Simulation run-through

The run-through of the simulations is shown in the following diagram:

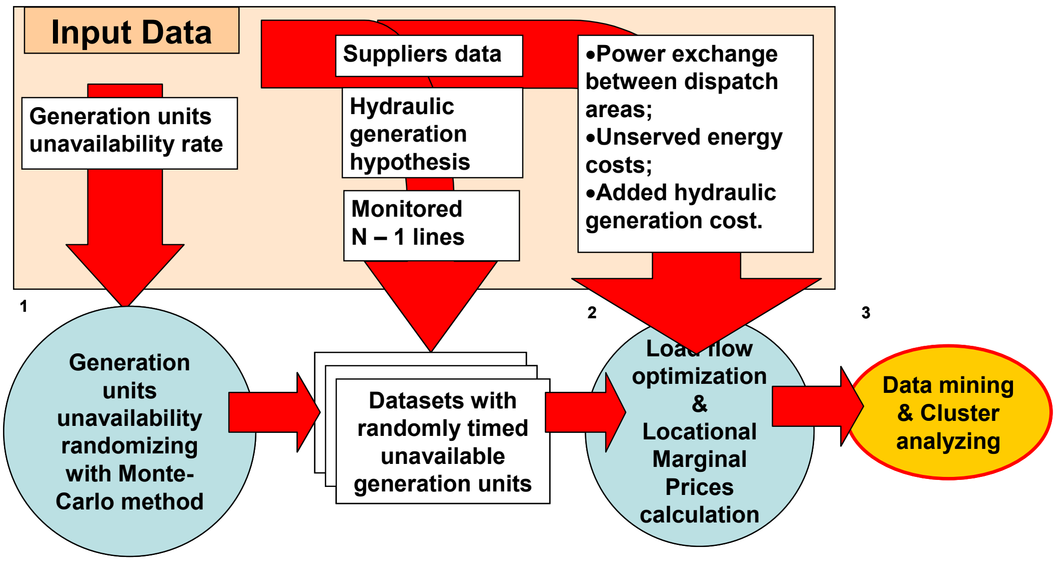


Figure 5

Simulations are carried out using the EDF's METRIS software, an OPF (Optimal Power Flow) probabilistic software which establishes an economic optimisation of the constrained electric system model under the DC approximation of power flows.

The process of calculation consists of three stages. The first two (blue bubbles) are carried out using METRIS whereas in stage 3 (orange bubble), data analysis software is used. Here is a brief description of the stages:

1. Before starting up the optimisation calculations, for a given level of consumption, METRIS generates a large number of unavailability situations of the generating units, on the basis of the unavailability factors of these units. This operation is carried out using the Monte Carlo method.

2. For each group unavailability situation, METRIS calculates a load flow solution while minimizing the overall operating cost of the system. The result of each simulation contains Locational Marginal Price values for each node. The more detailed formulation of the optimisation criteria used in METRIS is given in Appendix 1.

3. All of the Locational Marginal Prices are exposed to hierarchical classification based on Ward's Criteria.

Following the calculations, all the nodes are grouped into classes the number of which can be defined in advance. The detailed formulation of the method is given in the Appendix 2.

The classification of the nodes, based only on the average values of the LMPs (with respect to the generation units unavailability situations), although very attractive because of its simplicity, proves unsuitable because of the loss of a great amount of information on the behaviour of the LMPs.

As an example, the following diagram shows the performance of the LMPs in the various generation unit unavailability situations, in the 5 different nodes.

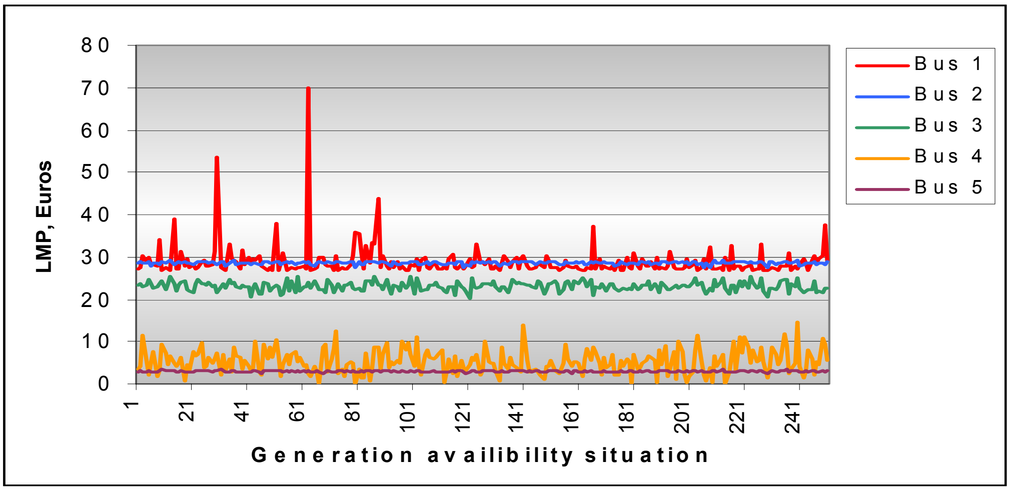


Figure 6

Simulation results

First example: Search for consistent electricity price zones on the Iberian Peninsula

The purpose of this example is to demonstrate how it is possible to break down the electrical system on the Iberian Peninsula into zones where the electricity prices are assumed to be consistent, by applying the method described above.

By gradually increasing the number of desired zones, phenomena specific to the Iberian Peninsula and electrical system begin to appear. The classes are arranged in the increasing order of the average LMPs. Constrained lines are also shown in the diagrams.

The following diagrams present the results of simulations made for the case of the Spanish and Portuguese electricity systems during the on-peak hours on winter period.

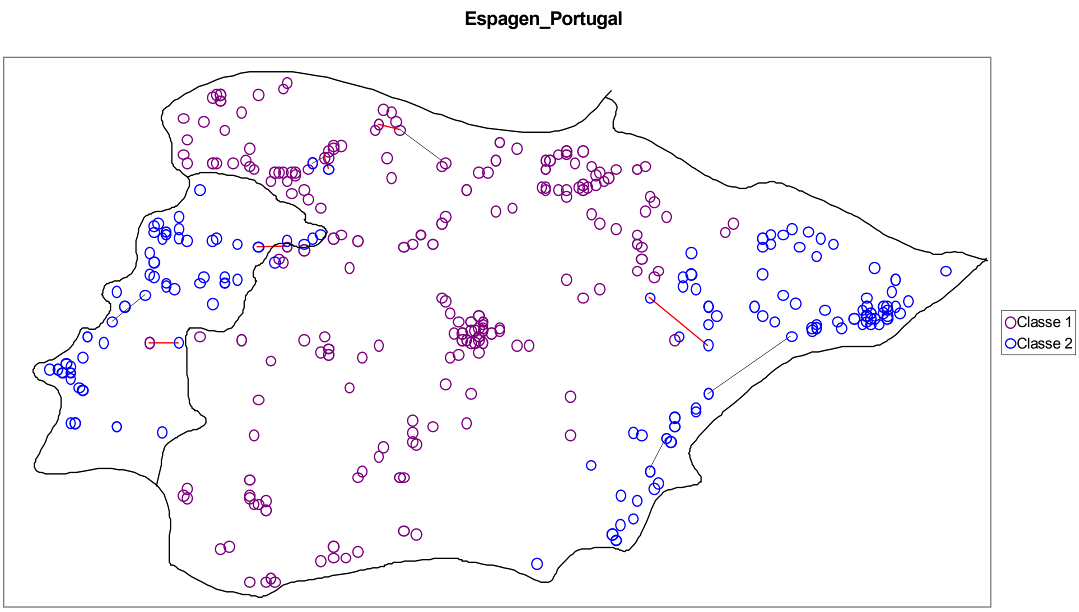


Figure 7

Separation into 2 classes: Portugal can be seen clearly because the price of electricity during the peak winter period is greater than that in Spain. Similarly, Eastern Spain makes far greater use of fuel-fired plants, contributing to the increased electricity price in this area. The constraint in northern Spain is not perceptible in this classification.

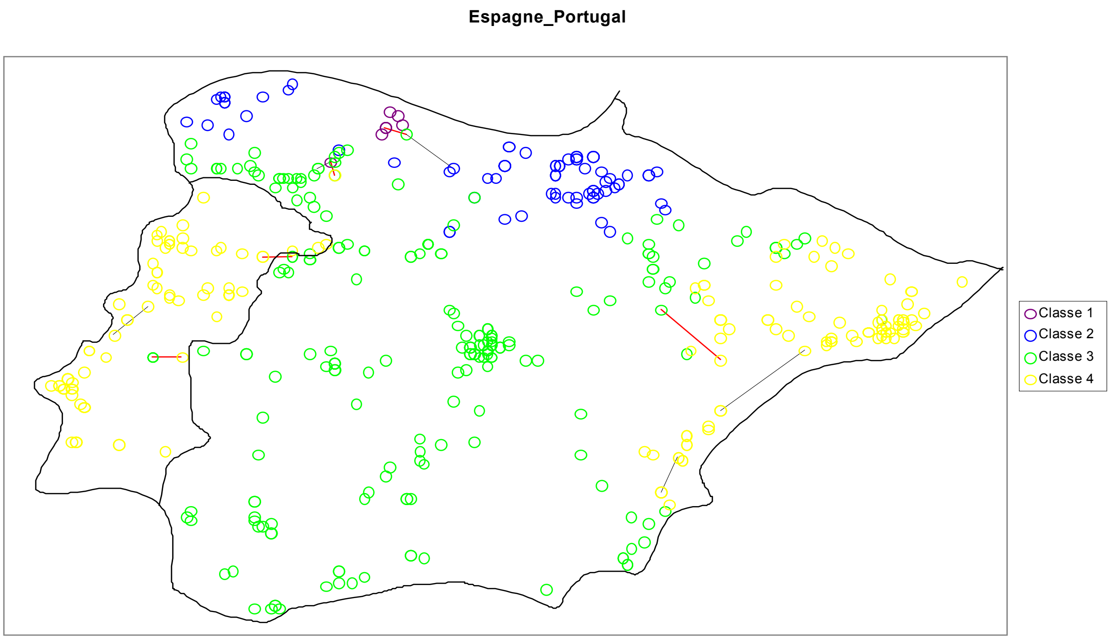


Figure 8:

Separation into 4 classes: In northern Spain, electricity prices are relatively moderate thanks to the great number of coal-fired plants in this region.

Concerning parts of the nodes in this region (class 1), problems of generated power evacuation have been observed (congestions on the lines leading to the southeast of the country), causing electricity prices to drop at the connection nodes of the plants in question.

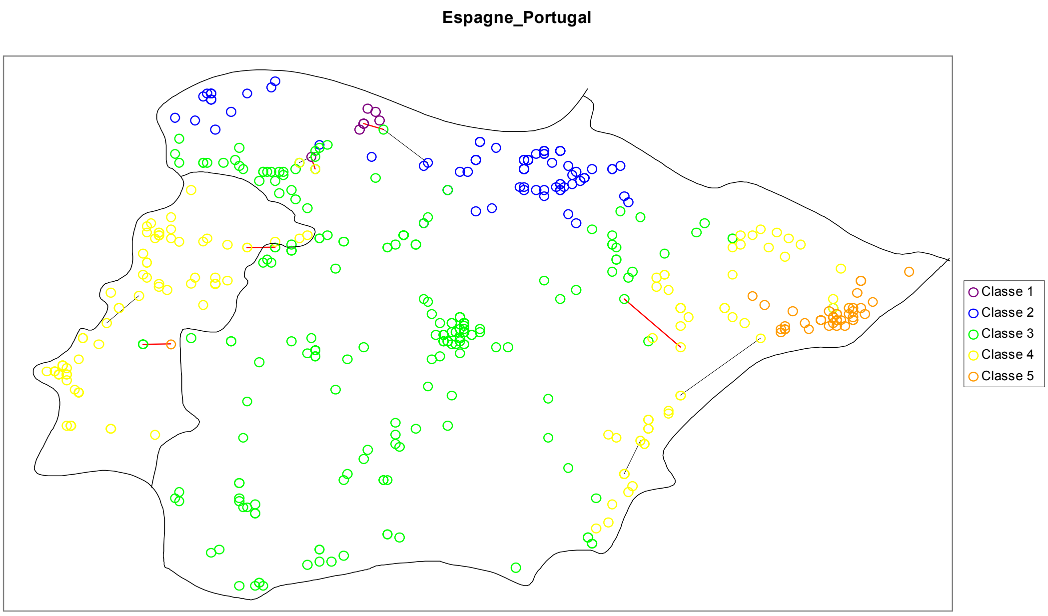


Figure 9:

Separation into 5 classes: In addition to the areas detected previously, there is also the Barcelona area.

Consumption is very high in this area, which essentially employs expensive fuel-fired plants, In addition, because it is at the intersection of the energy flows (North-South versus West-East), the region is systematically congested.

By separating the nodes into 6 classes, we have the same image with only one different node in the Barcelona region. At this node, the LMP is well below that of the surroundings, probably because of problems of the underlying 220 kV system supply from a transformer substation located on a powerful 400 kV line leading in from France.

Apart from this local phenomenon, changing the number of classes from 5 to 6 has not added any precision to the identification of the electricity system LMP consistent zones on the Iberian Peninsula. However, the optimum number of classes from the study in question appears to be 5.

Second example: Analysis of a border zone

This type of the study could be qualified as "local". It consists of plotting a border around the price areas on each side of a given constraint, for instance, to form the fundamentals of the system.

The advantage of this type of study is to compare the results obtained in this way with the price zone contours resulting from the cross-border capacity allocation procedures currently operated by the European TSO on the congested interfaces.

As already mentioned, in the case of constraints in the interconnection lines, the separation between the price zones now coincide with the borders between the national dispatching zones which, in turn, coincide with the political borders.

This is the case for the France-Belgium, France-Germany, Germany-Netherlands and north Italian borders.

The following map reveals the offset between the existing price zones (black dotted line) and the zones that are defined by the basics of the electrical system for the case of an interface between two European countries.

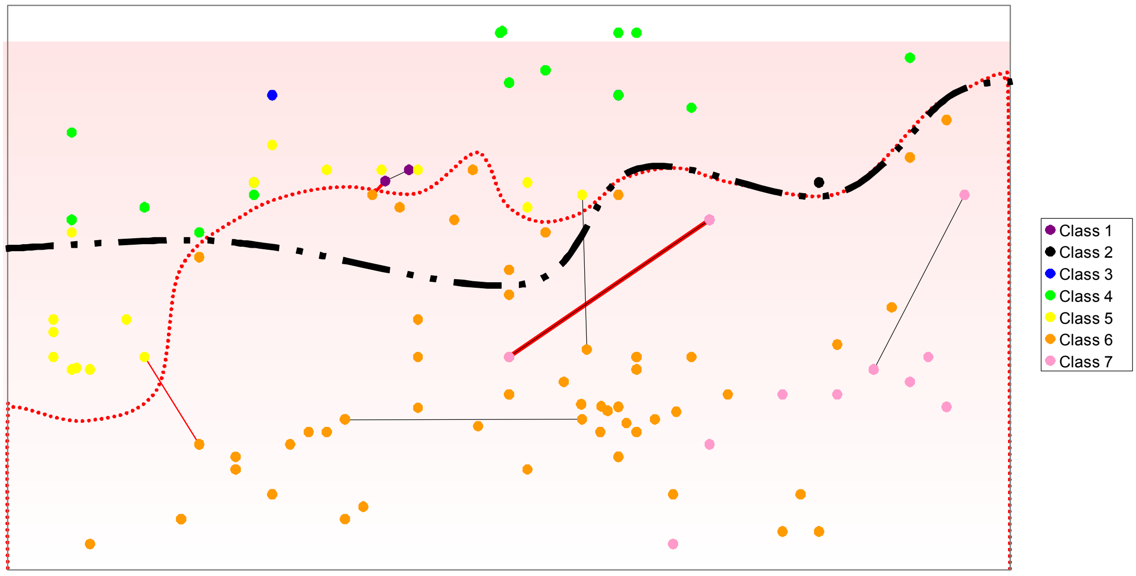


Figure 10

General remarks about the study examples

The examples given above are based on a simulation carried out for on-peak winter period.

However, the calculation of the Locational Marginal Prices is affected by many hypotheses (value of loads, the vagaries of group availability, network topology, etc). This means that their values vary enormously from one situation to another, particularly since network constraints bring in threshold effects: while the limits of the structures are not reached, the price values are all identical and as soon as an overload occurs, the situation is changed entirely, independently of the redispatching volume in question.

That is why the use of Locational Marginal Prices must be accompanied by sensitivity studies with respect to the main hypotheses and must take into account at least 4 hourly situations (winter and summer on- and off-peaks).

There is also the fact that classification is still a way of synthesizing information when many simulations have been carried out, but is insufficient in its own right and calls for detailed analysis of the constraints appearing in the network.

In addition to the unavailability of the production units, other types of random variables with exogenous magnitudes concerning the electricity system should be taken into consideration to increase the consistency level of the model. In particular, we are referring to the following phenomena:

- cold spell having a different effect on the regions being investigated;
- different hydraulic situation per hydraulic region;
- contrasting wind generation of electricity per region;
- modification to the rates of the fuel rates: coal, gas, petroleum;
- generic failure affecting certain equipment;
- significant change in the generation in a given area (aspects of power and technology);
- major change in consumption within a given zone;
- different scenarios of network reinforcement.

Conclusion

The use of LMP –based network nodes classification provides the rapid supply of guidelines for the initial analysis of a complex situation or a large-scale problem.

This concept can be used locally for investigating a connecting node from the investor point of view or more globally to characterize the structure of the European electricity market, no longer defined by geographical borders but by network constraints.

At local level, it makes possible to determine the impact of network constraints on producer remuneration, whether the unit is constrained on or off.

At the macro-economic level, the domestic electricity market, currently impeded by national borders, could eventually move closer to the structure defined by the network constraints. The weight and extension of this market integration are now unknown and only the scenarios can be considered at this stage.

The LMP –based network nodes classification on the continental shelf will nevertheless serve to measure the impact of the regional markets: could thorough integration lead to near uniformisation of prices on the continental shelf, or could new regional structures with highly differentiated prices appear?

On this point, several of the regional entities consisting of a number of European countries could change the competitive position of the main continental partners.

Appendices

Appendix 1: the METRIS model

A brief description of the linear program resolved in METRIS is given below. METRIS minimizes, in this way, the total cost of production, unserved energy and of the transactions, in complying with safety analysis (systematic testing of the loss of one or several transmission lines). It minimizes the following objective function:

$$\text{Min FO} = Min\left(\sum_{zones} \left(\text{Production cost} + \text{UE. Cost} \right) + \sum \pi_l \times (T_l^o - T_l) + \sum \pi_s \times T_s \right)$$

With:

UE cost : Unserved Energy cost

T_l^o : contractual value of the fixed-objective transaction

T_l : fixed-objective transaction effectively completed

π_l : cost of penalty for failing to comply with fixed-objective transaction

T_s : power exchanged as part of short term transaction

π_s : negotiation cost of short term transactions

In addition to this optimisation, each dispatching area is required to satisfy its production-consumption balance its own balance sheet:

$$Demand = \Pr oduction + UE + \sum \pm T_l + \sum \pm T_s$$

With UE: Unserved Energy

Globally we have:

Demand = Production + UE

The Locational Marginal Price at the node is referred to as $C_m^{AR}(s)$ representing the variation of the economic price of satisfying the total demand (minimized objective function) for an increase of 1MW in consumption at a given node. In other words, $C_m^{AR}(s)$ can be expressed as the drift of the objective function (OF) compared to demand d_s at node s, i.e.:

$$C_m^{AR}(s) = \frac{\partial}{\partial d_s} \text{(economic cost of satisfying the total demand)}$$

Appendix 2: statistical analysis

Descriptive statistics

The procedure used by SPAD carries out a hierarchical classification of a set of individuals characterized by their initial factorial coordinates. In the following, we detail the principle of factorial classification as well as the aggregation criterion used for defining the classes.

Main component analysis (ACP)

There are n individuals described by the values of p variables X1, X2,..., Xp. Each vector Xi of the characteristics (xi1,...,xip) of individual i is considered as a point in p-dimensional space. The principle of the method is to obtain an approximate representation of the clusters of n individuals in a space of p variables, in a subspace that is smaller (ideally, a dimension 2 subspace). This will be obtained by the projection of the n individuals into a subspace yet to be determined.

The projection space is chosen according to the following criterion, which is equivalent to distorting as little as possible the distances by the projection. The desired subspace having the dimension k is such that the average of the squares of the distances between the points and their projections are as small as possible. In other words, the inertia of the cluster projected onto the subspace must be maximised.

In more explicit terms, if we refer to the center of gravity of cluster N as g, the point whose coordinates are averages of the different variables:

$$g = (\overline{x1},\ldots,\overline{xj},\ldots,\overline{xp}) \quad \text{with} \quad \overline{xj} = \frac{1}{n} * \sum_{i=1}^{n} xij$$

the dispersion of the cluster around its center of gravity is measured by the total inertia of the cluster N, defined by:

$$I(N,g) = \frac{1}{n} * \sum_{i=1}^{n} \sum_{j=1}^{p} (xij - \overline{xj})^2 = \frac{1}{n} * \sum_{i=1}^{n} d^2(xi,g)$$

where d²(xi,g) represents the square of the distance from point xi to the center of gravity g.

The construction of the first main component becomes equivalent to seeking the projection straight line so that the loss of information is minimized; because in this case the "information" is the set of distances from point to point, i.e. the total inertia of the cluster, it means maximizing the inertia "explained" by the first main axis, which is the inertia of projections of points onto the straight line. If we refer to as y1,...,yi,...,yn the projections of points onto this straight line D and g* the associated center of gravity, this inertia will be expressed in the following form:

$$I(N,g) = \frac{1}{n} * \sum_{i=1}^{n} \sum_{j=1}^{p} (yij - \overline{yj})^2 = \frac{1}{n} * \sum_{i=1}^{n} d^2(yi,g^*)$$

Because the projections necessarily reduce the distances between points, this inertia is smaller than the total inertia of the cluster. The overall quality of the first main component is the ratio of the inertia explained by the first main axis with respect to the total inertia.

The principle used in the construction of the second main component is the same. What is more, because the main components are at right angles, there is no redundant information. This makes it easy to display the n individuals in a 2-dimensional space as generated by two of the main components. A representation like this then makes it possible to define the groups of individuals.

The ascending hierarchical classification method using the WARD criterion

This method allows the relatively rapid partitioning of the sets with relatively high cardinality into a number of classes k. It consists of locally optimising an inertia criterion. In the same way as previously, it is assumed that the individuals are points of R^p with a Euclidian distance. For any partition into k groups of a cluster of points, we can define g_1, ..., g_k, n_1, ..., n_k and I_1, ..., I_k, the centers of gravity, the numbers and the inertias of the k groups. The total inertia I of the n points around the global center of gravity g then equals the sum of the two terms : $I = I_{intra} + I_{inter}$, where I_{intra} is the intraclass inertia and I_{inter}, the interclass inertia (or cluster inertia of the k centers of gravity). By using the same notation as before, these terms can be expressed in the form:

$$I_{inter} = I(g1,...,gk) = \sum_{i=1}^{k} \frac{n_i}{n} * d^2(g_i, g) \quad \text{and} \quad I_{intra} = \sum_{i=1}^{k} \frac{n_i}{n} * I(N_i, g_i)$$

The classification criterion consists of searching for the partition in such a way that the intraclass inertia I_{intra} is minimal so as to have an average of very homogenous classes, expressed through the Ward criterion. When in the typology G_1, ..., G_k, we replace two classes G_r and G_s by their combination $G_r U G_s$, there is a decrease in the interclass inertia; this decrease is the Ward aggregation criterion.

$$D(G_r, G_s) = I(G_1,...,G_r,...,G_s,...,G_k) - I(G_1,...,G_r U G_s,...,G_k)$$

The hierarchical ascending classification method is iterative. At the current stage, there is a partition of all the individuals into k classes and the two classes are grouped together to minimize the Ward criterion. During this iteration, the inter-class inertia decreases in equivalent proportions. During the initial stage, each individual forms a class and the total inertia is then equal to the inter-class inertia. During the final stage, there is only one class and the inter-class inertia is therefore zero. The sum of the inter-class inertia losses of the various aggregation stages therefore equals the total inertia. At each stage, we calculate an index obtained by dividing the inter-class inertia lost by the total inertia.

The typology deemed to be satisfactory corresponds to the stage for which there is an abrupt increase in the index.