TRANSMISSION AND INTERCONNECTION NETWORKS

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Summary

Electricity appears to be an essential commodity wherever it is provided. Just look at the consequences of the major power disruptions that have occurred throughout the world, for example, New York in 1965, France in 1978, Quebec in 1998, etc. Also consider the impact of the first introduction of electricity due to rural electrification: light, refrigerators, TV, etc. One can see that electricity is absolutely necessary to economic development and quality of life.

The situation of developed countries is the result of a little more than one century of trials and errors, ingenious discoveries, technological progress, considerable investment and human passion for such a special product. Many (too many!) developing countries are still in the early stages, but they benefit from the experience of others, thanks to the extraordinary circulation of information and highly efficient international organizations that help virtually permanent forums of exchange.

The objective of this document is to explain how it works. To get an initial approach of the general organization of so-called power systems, to explain how the general architectures are chosen and to have a first look at the way decisions are made. We shall consider how environmental concerns are part and parcel of all these matters: visual impact of overhead lines, possible health effect of electromagnetic fields, etc. We have also sketched a historical background that should help readers to understand how we reached the present situation. In addition, we shall comment on the revolution that constituted the introduction of market forces in this activity, about a decade ago.

From the outset, and even now, power systems have been developed to meet economic efficiency and provide customers with a good product at a reasonable price. However, we must admit that it has also allowed parsimony as regards the various items of equipment necessary to generate, transmit and distribute electricity. We have to realize that, even before the concept was revealed to us, power systems have always contributed to sustainable development!

1. Introduction

Three types of networks are usually distinguished:

1. Major transmission and interconnection networks, joining up the large generation centers and main consumption centers, also linking large regions one with the other and even countries; the voltage levels of most of these networks are between 220 and 800 kV and only these networks are concerned by this article.
2. Sub-transmission networks, which, receiving energy from the preceding networks, convey it to the outskirts of small towns or within large cities, to groups of villages or to the premises of major industrial consumers; the voltage levels of these networks range from 45 to 160 kV.
3. Distribution networks which criss-cross the territory to reach residential customers and industrial consumers of medium size; the voltage levels of these networks range from medium voltage (between 4 and 45 kV) to low voltage (several hundred volts).

Whereas the function of the two latter types of network is easy to understand (criss-crossing the territory to convey energy to the smallest of customers), the function of major transmission systems is more complex, which is why we'll first dwell on this subject.

2. Role of Transmission and Interconnection Networks

2.1 Role of Time and Space

Among consumption goods, electrical energy is one utility that is made available to users in the fastest time. All that is done is to press a switch and the energy is provided instantaneously, from a power plant perhaps located a few hundred kilometers away. Both the order and transmission times are therefore practically nil.

This property obviously stems from the fact that electrical energy is conveyed without the simultaneous transport of matter, so that, instead of transport, the term used in French, one should indeed speak of transmission, the term referred to in English.

However, the absence of matter to be transported is also at the root of a major handicap: the impossibility of finding ways of **storing** this energy at reasonable cost prices. At a first glance, this handicap does not seem to favor the rapid availability of the power variations requested, since the setting up of stocks is precisely intended to absorb through time the consumption variations which the electricity output would be unable to meet. It is therefore paradoxical and, in some respects remarkable, that the least storable of consumption goods is also among those that feature the greatest ease of use. To obtain this performance, despite the practical impossibility of direct storage, two means of replacement are used:

- indirect storage, in practice in hydraulic form; its interest is such that, in many countries, pumped storage power stations have been built, these facilities providing a dual conversion electrical energy—hydraulic energy—electrical energy by storing intermediate hydraulic energy,
- general interconnection of the network which we will speak about later on in this document.

The general interconnection, in fact, uses the many generation and consumption centers to organize among them some compensation of their random factors or, to put it more simply, of their variations and thereby regulate not only overall consumption, but also the generation possibilities.

It is to be noted that the role of a stock, for an ordinary good, is precisely to regulate the unavoidable variations in generation and consumption, in such a way as to have a maximum chance of meeting consumption requirements. However, to do so, the stock uses time whereas the network interconnection uses space; in both cases, it concerns adapting the rate of generation to the rate of consumption. The stock means that one does not have to distribute a good at the *time* it is produced; the interconnection network means that a kilowatt-hour does not have to be distributed at the *place* where it is produced. There is consequently and obviously a time-space conversion to be made if one is to fully grasp the full meaning of the role of a power transmission system.

It is therefore only natural that two types of power transmission be distinguished:

- regular transmission, which links the generation areas and the consumption areas;
- compensatory transmission which depends, at a given time, on the spatial condition of consumption and generation; this type of transmission is fairly specific to electrical energy; it is distinguished from the foregoing in that the direction of transmission may be reversed on power lines whereas regular transmission always has the same direction.

This distinction must be made for the analysis, while considering that, in practice, the two types of transmission generally co-exist on the same physical supports, i.e. the lines of the major transmission and interconnection networks.

2.2 Regular Transmission

According to our definition, regular transmission goes from the generation centers to the consumption centers.

Electricity is not conveyed for the pleasure of it. An effort has always been made to build power plants in the vicinity of consumption areas. However, this is not always possible and two main reasons go to explain the existence of the regular transmission of electricity:

- hydro power sites cannot be displaced;
- power plants cannot always be built where the power producers would like to build them.

Let's take a closer look at these two ideas.

2.2.1 Transmission of Hydroelectric Energy

The facilities that a country has in the way of dams capable of using the energy potential of a hydro basin assumes that one is able either to transmit electrical energy to the major consumption centers, or to bring the corresponding consumption near the hydroelectric power plant. In France, for example, the country's high-capacity hydro power schemes were built in the Alps. This was followed, on one hand, by an industrial boom in this region (large Alpine valleys and the Rhone valley) and, on the other hand, by power transmission lines which exported the surplus electrical energy to the Paris region. However, today, the hydroelectric energy generated in the Alps or in the other regions has hardly increased, whereas consumption has increased steadily. This generated energy may therefore be more and more used on the site and the regular transmission of electric power which, by definition, covers major distances between hydroelectric sites and consumption areas, is gradually disappearing in France and, more generally speaking, in most highly industrialized countries. This does not hold true in other countries where the non-harnessed hydroelectric potential is still considerable. Several thousand terawatt-hours per year are yet to be exploited in the world.

These immense resources, sometimes concentrated along a few main rivers, explain the development of regular transmission of several thousand megawatts over a few thousand kilometers, something that is not be seen on the old European continent:

- in Quebec, for example, James Bay has a power potential of 18 000 MW the largest part of which must be conveyed over a distance of 1200 km;
- in South Africa, the energy generated on the Cabora-Bassa site (installed capacity 1700 MW) is conveyed over a distance of 1350 km;
- in Brazil, 4000 to 6000 MW are transmitted over a distance of 2500 km.

2.2.2 Difficulty in Building Thermal Power Plants near Consumption Centers

The problem of cooling water was a considerable constraint at the beginning of the development of thermal generation: power plants had to be built in areas where there were sufficient amounts of water capable of cooling the steam in the condenser. This was at a time when thermal units were built along the main rivers and on coastal sites. Any surplus energy that was not consumed on site was conveyed back up to the consumption centers via the transmission system.

This problem has now certainly evolved: on the one hand, because the major rivers offer no further cooling possibilities and, on the other hand, because the air cooling technique is now wholly mastered, freeing the problem of choosing the generation site from the constraint of having large quantities of cooling water.

One might therefore think that nothing further prevents power plants from being built as close as possible to consumption areas. However, national and regional development and land use constraints, as well as the natural obligation of dealing with environmental concerns necessarily limit the realization of a policy for the construction of power plants resulting in a reduced transmission of electrical energy.

2.2.3 Summary

There is no reason to develop, in the countries of the old world, the major and regular transmission of electricity over large distances. On the other hand, some reasons, which have evolved over time, and which range from the exploitation of hydroelectric resources to national and regional development, have led and are leading to organizing a minimum of regular transmission. Transmission distances are therefore relatively moderate, since they are around one hundred kilometers on average. There is no reason for these figures to change to any great extent in the future, because a certain regional balance between generation and consumption will likely be conserved.

In other regions of the world where power plants can be located for away from areas of consumption (for example, in China, Africa, Quebec and Russia, etc.), regular transmission remains substantial.

2.3 Compensatory Transmission

2.3.1 General

The interest of compensatory power exchanges stems from the fact that the unavoidable variations of generation or consumption are lower, in relative value, as the considered network is large. This phenomenon results from a certain statistical compensation of variations due to the random component of consumption and generation (unit outages), as well as from a certain deterministic compensation due to the non-simultaneity of certain components of consumption (shifting of peak hours between the different regions of the same country) and of generation (thermal–hydraulic compensation). This phenomenon is general enough so that it is needless to dwell further on the subject; it is that which usually makes the existence of stocks profitable and which justifies, in power networks, the grouping of all local consumption, as well as all local generation, to form the real pooling of resources and needs.

Since we cannot go into all the components of this compensation, we will only mention the main ones, in other words, those which are linked to the economy of generating facilities and to their operation.

2.3.2 Compensation of Generating Set Outages

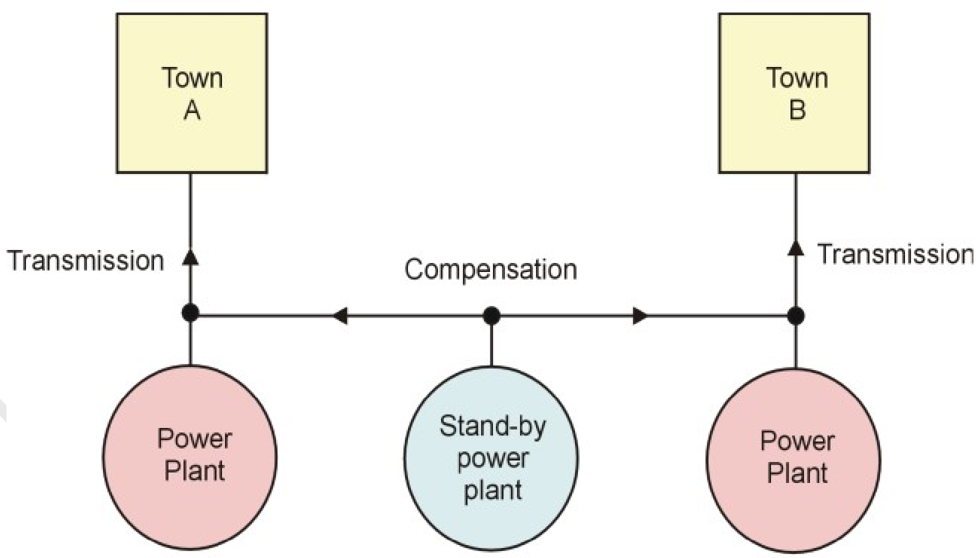

Figure 1: Transmission and Compensation Lines.

Let us suppose that a thermal power plant, with capacity P supplies town A (Figure 1) the maximum consumption of which is also P and that, 100 km farther away, a similar power plant supplies town B with the same maximum consumption. Since one of the properties of a thermal generation set is that it might break down, each town must protect itself from this risk by having an additional set on stand-by; this results in the idea of having the same set on stand-by for both towns and of erecting a line to link them. In this case, we have a power network consisting of two transmission lines and one compensatory line.

More generally, accidental set outages make it necessary to over-equip a network with generating facilities, that is, in providing an installed capacity that is appreciably higher than the maximum foreseen consumption. This over-equipment may be lower, in relative value, the larger the considered network, in other words, the higher the total number of generating sets. Consequently, the interconnection of two previously isolated networks makes it possible to reduce the over-equipment that each of them has to keep, in order to ensure that peak consumption is met with a given probability.

Obviously, the interconnection line itself costs a certain amount of money and it is important to make sure that its cost is less than the value of the generation equipment reduction that it makes possible. However, in fact, the investment cost of a generation capacity of one megawatt is equivalent to that of conveying this megawatt via overhead lines over a distance of 10 000 km. One can understand why there is considerable interest in the interconnection, rather than develop local generation reserves.

2.3.3 Economical Management of Generating Facilities

Electricity consumption levels vary considerably during the 8760 hours of a year, showing differences of about 1 to 1.2 during the same winter day and about 1 to 2 between the winter peak period and a slack period in summer.

For each of these periods, energy must be provided at least cost. But the various power plants have highly different generation costs, ranging from a nil cost for run-of-river hydro power plants to a cost of about a quarter US $ per kilowatt-hour for gas turbines. For each hour of the year, the economical management of generating facilities therefore consists in covering the power to be generated by using the most cost-effective generating sets.

That being the case, one of the roles of the network, for each of the possible situations, is to convey the energy from the least expensive available power plants to the consumption areas. Let us suppose, for example, we have a power plant near a city; if this power facility costs a great deal to operate, it will only be used during peak load periods. Outside these hours, the extra high voltage network will supply the city from another power plant featuring better cost-effectiveness. Once more, we can see the hub aspect of the power system, responsible at all times for *collecting energy where it is least expensive and then conveying it to where there is a demand for it*.

2.3.4 Remark

These different types of compensatory transmission are obviously not limited to the national grid, but go right across frontiers to form a genuine common market of electrical energy, a topic which we will talk about again further on in this paper. The chart in Figure 2 shows, for example, the high level of energy exchanges that took place in 1998 between the different countries of Europe. We can see that Switzerland plays a major role as a hub and the same is true for France.

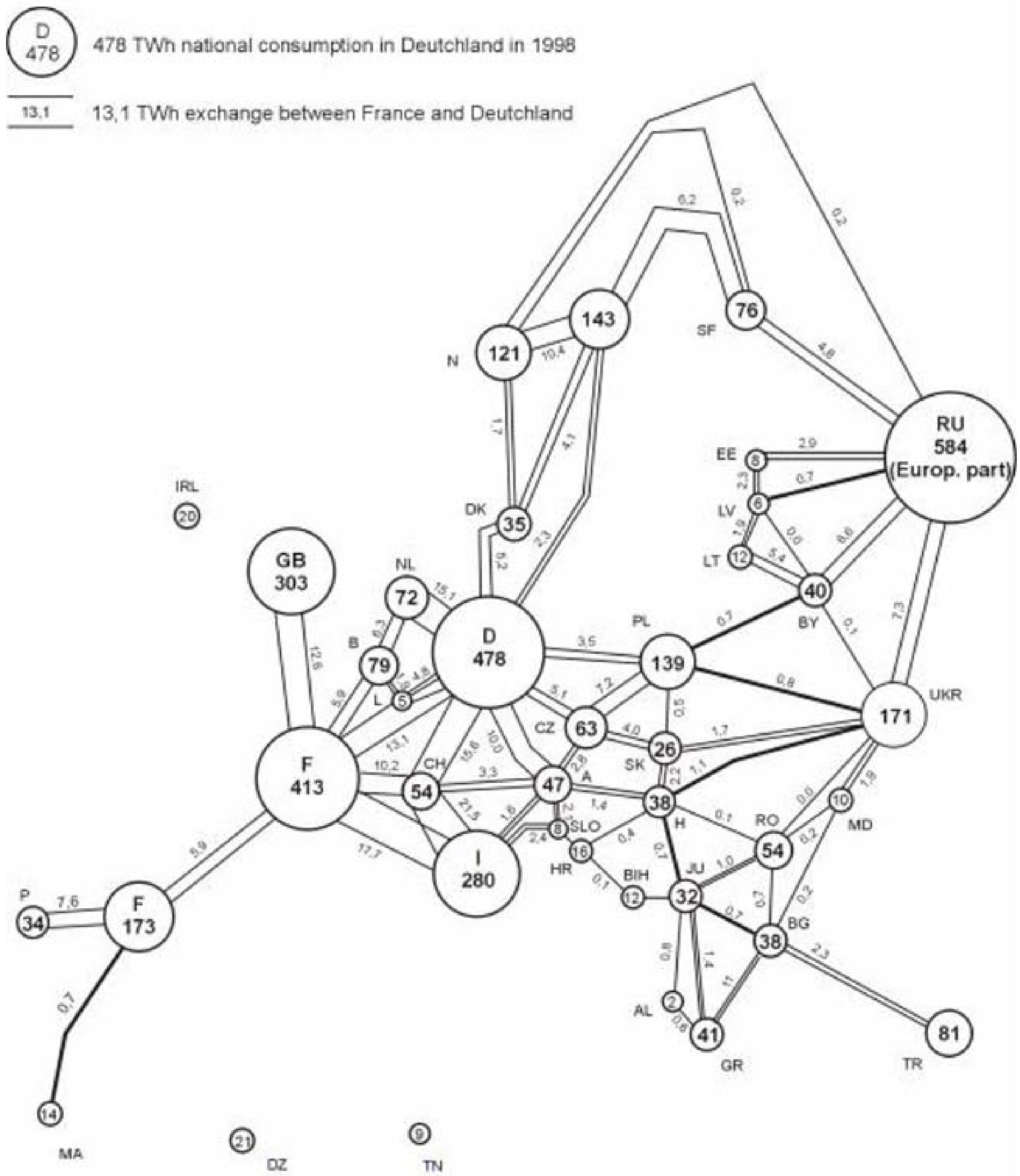

Figure 2: Electrical energy exchanges in Europe in 1998.

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Biographical Sketch

François Meslier was born in 1949, married, with three children. IEEE Senior Member, Lauréat de la Médaille Blondel. Chairman of CIGRE Study Committee 37 "Power System Planning and Devlopment". About 200 international publications in the field of power systems. Alumnus of Ecole Polytechnique de Paris (1969); Doctor in Management (Paris IX Dauphine, 1972). Project Manager in 1972 at the R and D division of EDF, to start with, his various duties in the following years gave him a sound technical and managerial background in the field of power systems: optimization methods, load forecasting techniques, planning methods and studies of EHV systems, development of subtransmission and distribution networks, EMS and DMS, metering, protection and control. He was in charge of the "Power Systems Studies" Department of the R and D division in 1990, 200 people, mainly engineers, in charge of the key power systems activities of EDF. In 1993, he became Director of one of the 14 French Business Units, in charge of generation, transmission and sales to large customers and Distribution Business Units. In 1995, he became Director of Transmission for EDF. Since the end of 1999, he is Managing Director of the French Overseas Departments.