Smart grid's application to projects of Tractebel Engineering France

XINRAN GUO
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Xinran GUO

Electrical Power Engineering, KTH

Hydro-Electro-Mécanique Section,

Tractebel Engineering France
Abstract

Nowadays, we hear much about smart grids as a promising idea that will have a direct impact on our life of tomorrow. Research, articles and standards are also numerous on this subject. Among them, IEC 61850 is an important standard about communication which could have a big influence on electrical substations or even power plants in the future. However, the feasibility of this standard has been little investigated.

This study has been done with Tractebel Engineering France, which is a branch of GDF Suez. They have good expertise on hydro power plant, but their projects can also cover electrical substations and electrical transmission lines. Smart grid’s development can have direct impacts on their activities.

The study presents firstly the different aspects of smart grid, in order to know the logic of motivations and the interesting points for the company. A certain emphasis has been put on the electrical grid functioning aspect as well as renewable energies, because they seem to be especially important for Tractebel.

Secondly, the study is focused on the main aim of this article, the feasibility of IEC 61850 to a substation of Tractebel’s Kaléta project. A presentation and analysis of essential notions of the standard 61850 has been done in chapter VII. In the following chapters, the study tries to make a judgment of the feasibility by analyzing the aspects of software, modeling and practical functioning of the substation.

The study concludes that despite the fact that IEC 61850 seems to be the standard of the future, it is still premature today for Tractebel to use it in the case of Kaléta. Due to the independent software tools’ complexity and the lack of interoperability between different components, the modeling process remains complicated if we don’t want to choose a software program provided by a specific equipment supplier. Moreover, the functioning of an IEC 61850 substation requires new skills for the staff, which could be another practical problem for Kaléta.
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I. Introduction

Nowadays, we hear much about smart grids as a promising idea that will have a direct impact on our life of tomorrow. Research, articles and presentations are so numerous on this subject that as soon as we are a little more interested in this area, we find ourselves very quickly faced to a flood of information. However there are very different views and expectations on the smart grid, which does not have single definition. If we believe what manufacturers say, we could believe that all the problems are solved, and it is enough to implement electrical grids of the future as soon as possible; while some researchers think there are still too many difficulties. It’s why it is important to have a global and critical vision on the concepts related to the smart grid, in order to respond to the following questions: what is the smart grid? What is the logic of development? What is the perspective of the future? What will be the impact? Etc.

For a company like Tractebel Engineering France which has a lot of activities in the electric power sector, and more specifically the HEM (hydro-mechanical-electrical) section who performs work mainly on hydroelectric power, it is important to know smart grids and its potential impacts.

This article is divided into two major parts. The first part (chapters III - VII) will focus on a general study of smart grids, trying to find in particular the logic and the order of motivations of this development, as well as a perspective of the future. A certain emphasis will be put on the operation of the power grid and green energy, because they are more likely to concern Tractebel. The second part (chapters VIII - X) is specifically on the study of the standard IEC 61850, which is a part of the concepts of smart grids and that could impact directly the activities of the pole HEM, on the achievements of electrical substations, and eventually on the hydroelectric plants later.

Thus, the aim of this is article is mainly about:

1. To identify the aspects and technologies of smart grids that can be interesting for Tractebel Engineering France; to help engineers of the company to give advices about smart grid to the clients.
2. To estimate the feasibility of application of the standard IEC 61850 to one electrical substation in Kaléta project, where Tractebel Engineering is responsible for feasibility, technical control and supervision.
II. Smart Grid, presentation of the problem

To identify interesting aspects and technologies of smart grid for Tractebel Engineering, it’s obviously important to firstly understand the logic of smart grid’s development, so that we can have a general view of its background and motivations. Classifying different motivations is especially important here, because nowadays, smart grid involves a lot of notions and technologies, which could turn out to be confusing if we don’t sort them and have a clear view on them.

II.1. Background and motivations

There are many reasons for the development of Smart Grids nowadays. The liberalization of energy market, a better functioning of power systems, environmental constraints and economic or political interests can be considered as main motivations.

II.1.1. Motivation 1: liberalization of energy market

Historically, during the 20th century in developed countries, the magnitude of the investments and the complexity of planning and management in the electrical energy sector demanded a monopoly model. In addition, a public monopoly, with centralized production architecture, was ideal at this time to respond to needs such as continuity of service or the fast development of networks [2].

However, while state enterprises are behaving correctly, this monopolistic and vertically integrated model is questioned because there is a growing awareness in the 1980s of their possible downsides, among which we can mention for example: excessive costs, low quality of service, bad investment decisions or a lack of innovation [3]. In this context, the liberalization of the market and a sectorial decomposition are put forward, driven in particular by political or economic interests.

With regard to Europe, in 1996 the European Parliament decided to create a competitive electricity market. A series of directives and national laws would be implemented
later. This deregulation led to a glaring change in the operation of electricity networks as new players arrived, and the monopoly model of electrical system disappeared gradually. The classic way of the electricity supply management was no longer able to follow this evolution. Thus, new requirements appeared and a smarter grid seemed necessary.

It is interesting here to note that at the time of the discussion on the opening of the electricity market, a price drop for consumers was considered as a weighty argument [2]. However, it appeared subsequently that the realization of this drop become unlikely. Of course, that does not mean that Smart Grids will be unsatisfactory, because nowadays, the fall in prices does not represent all of the objectives.

II.1.2. Motivation 2: A request for a better functioning of electrical networks

In 2003, a power outage left parts of Canada and the Eastern United States in the darkness. In 2004, a large power outage occurred in much of Western Europe. The multiple facts indicate that with the liberalization of energy market, the current electricity grids appear to become increasingly fragile, knowing that historically this was not quite the case. Therefore, the United States began to put emphasis on the “self-healing” character of electric networks [4]. In other words, a better reliability becomes paramount in this context.

In reality, apart large-scale power outages that have marked the spirits, there are a very large number of short disturbances that can also cause major economic disadvantages. A study conducted by Lawrence Berkeley National Laboratory reported that unreliable electrical systems cost 80 billion dollars per year in the United States [5].

Over time, other criteria on the functioning of the electricity networks are needed: reduction of peaks of consumption and reduction of losses in transmission and distribution networks. These requirements involve new technologies and standards.

II.1.3. Motivation 3: Environmental Constraints

By adopting, in 2009, the objectives of the 'three 20 targets' [6], the countries of the European Union engaged in a collective effort to achieve by 2020 the following goals:

- To reduce emissions of greenhouse gases by 20% relative to 1990 by 2020,
- To increase energy efficiency to save 20% of energy consumption relative to 1990 by 2020.
• To reach 20% of renewable energy in the total energy consumption in the EU by 2020.

Regarding France, the objectives to be achieved are as follows [6]:

• The electricity produced by renewable energy (hydro power not included) should represent 23% of French consumption in 2025, knowing that it is 2.8% today.
• Electricity from nuclear power should represent a 50% share in 2025, knowing that it is 74% today.
• The share of thermal electricity is expected to decrease from 11% to 2.8% by 2025. (The share of hydropower should nearly be constant, around 10%)

Thus, significant changes to electrical grids become necessary in order to integrate renewable energy. Energy of this nature often involves an intermittent and decentralized production, and furthermore, production capacity, compared with conventional generators, is rather low per unit, which makes the network management much more complex compared to the past. For all these reasons, it is necessary to have a network that is able to manage these different sources of generation in an intelligent manner, i.e. integrating the most possible green energy while maintaining the quality of electricity and the stability of the network.

Indeed, the word 'smart' can take different meanings depending on the context. For example, it can mean the "self-healing" character of the network as mentioned previously. Here it rather refers to the ability to integrate and manage renewable energy. It is therefore important to define clearly what the intelligence of the network is later. (See part II.2. Definition of Smart Grid)

II.1.4. Motivation 4: economic aspect

In 2008, Morgan Stanley estimates that the annual world market for Smart Grid could reach 40 billion dollars in 2014. Specifically, demand side management equipment would represent about 20% of the market, metering systems would occupy 20%, and for the rest, 60% is left to the network equipment [7].

For the same forecast for 2014, McKinsey estimated in 2010 that the figure would be between 15 and 31 billion USD [7].

Regarding Gimélec (Groupement des industries de l’équipement électrique, du contrôle-commande et des services associés), it considers that the value of the world market would be between 12 and 50 billion euros per year by 2020 [8].
Actually, according to the defined methods and perimeters, we can have a pretty large difference on the estimation of the market potential, but the importance of the economic aspect of Smart Grid is undeniable. According to [7], only the replacement of conventional meters by smart meters in Europe and the United States already represents a market of more than 50 billion USD. This could partially explain why the meter replacement appears to become a political priority, especially in a context of economic recession, knowing that meters are certainly not the most complex equipment of intelligent grids.

II.2. Definitions of Smart Grids

So far, we talked about different motivations of smart grid’s development, but what is exactly smart grid? Actually, in the literature, there isn’t a single definition of Smart Grids. For example, in the definition used in the United States (U.S. Department of Energy), the security of the electrical network is put forward while in the European definition (European Technology Platform), a greater emphasis is placed on the integration of green energy sources. The French definition of Smart Grids according to the Ministry of Sustainable Development is as follows [7]:

“Power grid that is capable of handling the optimum production/consumption balance in an increasingly complex environment. That is to say:

- There should be an increasing use of intermittent energy sources, and also decentralized productions;
- The grid should be able to deal with the needs of controlling consumption, peak load management and the improvement of energy efficiency;
- There should be a management of the multiplicity of actors, in an environment of liberalization of energy markets.”

Despite the fact that the definitions are different according to the expectations of the regions and countries, of course there are still some common properties that electrical networks must achieve [9]:

- They should be able of self-healing after supply disruptions.
- They should allow the active participation of consumers.
- They should have protection against the physical and cyber-attacks.
- It’s necessary to provide quality energy to meet the different needs.
- They should be able to integrate different generations and storage options.
- They should allow integration of new products, services and markets.

It is necessary to point out that the theoretical aspects of the definitions of Smart Grids still remain as some objectives to be achieved in the future. In other words, many challenges are still there, before concluding that "Smart Grids" will perform well their functions. Thus, in the following chapters, we will analyze the development and implementation of the intelligent electrical networks with a critical viewpoint.
III. Adaptation to a liberalized energy market

Historically, the management of electricity is quite different from that of today, such as what is indicated in part II.1. With regard to the reliability of the networks, the monopoly model is rather well suited. However, for economic and political reasons, as well as waiting for a decline in electricity price for consumers, a market open to competition is created. This opening of the market is made possible partly by technologies, in particular computing progression, because nowadays, the necessary investments in the sector are no longer the same scale as a time where only states were capable of managing large projects [2].

However, saying that this new market is necessarily better seems to be premature. Indeed, there remains especially the challenge of managing the multiplicity of actors, since electrical networks require a balance between production and consumption at every moment and a respect of the capacity of transmission of power lines. Thus, this task is made much more complicated with the arrival of new players. Another fact is that the decline in prices seems increasingly unrealistic, while it was hoped and expected at the beginning of the reforms.

Of course, there are also facts which are in favor of this liberalized market. For example, as we are interested more and more to the problem of climate change, it appears that this market could give incentives to the reduction of greenhouse gas emissions, including through the active participation of companies who are interested in green energy and which would not return in this sector if it did not reform. From another point of view, in the case of Europe, increasing production of renewable energy will require a more active coordination between states having different market systems, which will contribute to the outcome of a unified European market in long-term [10].

Thus, managing well the liberalized market becomes a primary mission of Smart Grids. Later in this chapter, we'll talk about the problem of the management of stakeholders and the possibility of the active participation of consumers.

The actors in the electricity market can be classified as follows: producer-supplier of electricity, transmission system operators, distribution system operators, consumers and the regulation authority. Electricity supplier is not to be confused with the producer, because the
supplier can feed the end customers from the energy he produces, but also from the energy he purchases from producers. In the French case, it existed until December 31, 2012, 19 providers offering service to non-residential customers, 9 of them also offer electricity to residential customers [11].

III.1. A European management

With regard to Europe, in the context of the creation of energy market, a management between different European countries seems to be necessary. Indeed, nowadays, it lacks sufficiently coordinated decisions between states; a flagrant example is that it happens to have a duality of energy supply systems at state borders [12].

Moreover, although there are principles of coordination, due to different ways of managing networks in different countries, the same management principle could prove to be efficient or not according to the country. In other words, European management could be more complicated and delicate than what it seemed to be. An example might be load shedding during peak load periods: with the aim of smoothing consumption peaks, a way of doing is to compensate consumers if they participate to the load shedding. However, according to a period which can be more or less long, the load shedding would have different values, so that the way to pay consumers should be nuanced. This is possible in a classic centralized market, but more complicated in the current context with the liberalized market. In France, from this point of view, we have the advantage of having a strong manager as RTE (Réseau de Transport d’Electricité, French transmission system operator), in order to make this kind of operation efficient, but this is not the case for all European countries [12].

Despite difficulties, there are attempts and efforts between countries, or under the direction of the European Union, to create a European market with quality. With regard to France, a Franco-German infra-day market must be created, hoping that this would lead to a better capacity allocation mechanism [13]. It means therefore a closer cooperation between transmission system operators. Better risk management in very short term, especially for the integration of renewable energy into main grids, could be achieved through this integrated market, knowing that renewable energy can make conventional networks fragile and unstable. If we follow this Franco-German logic in the European case, it is clear that Europe is going to be increasingly interconnected in the future, and management challenges will multiply.

The creation of a coordinated European market is not only a matter of legislation. Apart from agreements, guidelines or standards, there are also technological advances that are expected, they are obviously essential for such a project. Actually, most of the technological solutions are not only the problem of the market, since other problems, as the reliability or safety of electrical grids, have great importance in the concept of Smart Grids. However, these technological progresses could contribute directly or indirectly to the improvement of the
market management. We can take the example of the information system: by improving the information system, there may be less information asymmetry in the market. Because more generally, information asymmetry that exists in current electricity market may decrease the market effectiveness, and this can lead to a competitive price that is above the marginal cost, or to a waiting game when it comes to decide new investments. A system capable of making available data can increase efficiency in the allocation, as happens to optimize its price according to the law of supply and demand. In addition, a more rapid response to the demand for energy at a lower cost becomes possible, which also increases the production efficiency [14]. In addition, a better circulation of information obviously means a more harmonious coordination between different grid operators, and therefore a positive effect on the construction of the European market.

So far, we have mentioned briefly that the creation and management of a European market including legislative, political or technological aspects. There is also another important aspect that has not been treated, it is the economic aspect. Economic challenges and opportunities exist simultaneously and they can further complicate the situation. At this state, we simply give a few examples below:

As the market transforms and is supposed to become more and more intelligent, many companies see economic interests there. It is for instance the case for companies offering IT solutions since Smart Grids also assume a more sophisticated communication and information network. This also brings a challenge to the grid operator since technically, it is essential to implement a device capable to integrate different components developed by different companies, while maintaining the reliability of the grid [8].

Concerning the challenges, there is now a program called European Electricity Grids Initiative in order to supervise better the creation of the European market. According to this program, there are one billion euros missing in the next 10 years for the construction of the market. Obviously, it is not an insurmountable financial barrier, however, once again, this problem, like many others, requires a coordinated work between European states [8].

Despite the challenges, Europe seems to be determined to continue on this path of reform in the electricity sector. Therefore, we can ask the question, is this really worth it? It is almost certain that electricity prices will not fall with the opening of the market, contrary to the initial expectations of this reform. So what are the motivations for the continuation of this reform?

Indeed, during the development of Smart Grids, there are some goals that are unrealistic, but there are also new criteria that appear and become possible to fill even if they are not necessarily the original intentions. This is also the case for the European market.
Nowadays, to achieve the 'three 20 target' objective by 2020, European countries are somehow forced to work together, because the electricity production from renewable energy sources has often an intermittent nature, this poses a major challenge for the grids. If countries are now well interconnected and capable to work effectively when there is too much wind in Germany, for example, France can absorb it, and so we maximize the use of "green" energy.

Another interest of this interconnection between countries could be the reliability of power supply: for example, during the storm Klaus in the southwest of France, the city of Perpignan has been powered from Spain for 5 days [8].

III.2. A national management

The European directives concerning the establishment of the European energy market are transposed into French law by Parliament, to ensure the good introduction of new operating rules.

Public stakeholders in the electricity market are as follows:

- **CRE** (Commission de régulation de l’énergie), **l’Autorité de la Concurrence** and **DGCCRF** (Direction Générale de la Concurrence, de la Consommation et de la Répression des Fraudes) are independent authorities which ensure the compliance of the new rules of the market.

- **Producers** and **suppliers** of electricity are actually many; there are many small producers or suppliers as well as giants like **EDF** (*Electricité de France*) and **GDF** (*Gaz de France*). As mentioned previously, the electricity provider is not to be confused with the producer, he can feed the end customers from the energy he produces, but also from the energy he purchases from producers.

- **RTE** is the transmission system operator. Its mission is the operation, maintenance and development of the high voltage grid. It must ensure the good functioning and the safety of the electrical system. It carries electricity from vendors to consumers, and consumers can include here electricity distributors or industrialists who are directly connected to the transmission grids [15].

- **Distributor** in France is **ERDF**, which is a subsidiary of EDF. It provides about 95% of the electricity supply, the remaining 5% are shared by 160 local
distribution companies that have their activities in approximately 2500 municipalities [16].

- The energy mediator is a person who recommends solutions to disputes arising from the execution of contracts between consumers and energy suppliers, and he participates to inform electricity consumers their rights [17].

III.3. Presentation of metering system

In order to have control of the demand and active consumers who may participate in the electric energy market, a new metering system is necessary in the concepts of Smart Grids. Metering system includes three parts: the communicating meters, the communication infrastructure and the information system [18].

According to the definition of [8], generally, smart meters should be able to:

- Manage the classical functions of energy consumption measurement and variable pricing (i.e. at least the varying pricing for peak hours / off-peak hours, and in long term, a pricing even more flexible and dynamic if possible).
- Measure the produced energy; handle the power in transmission; drive the load curve.
- Achieve two-way communications, be controlled remotely.
- Easily give the consumers a better apprehension of theirs consumption.

These metering systems are supposed to be benefiting both for operators and consumers. Grid operators can for example drive more directly consumption demand through flexible pricing, and therefore they can achieve smoothing of consumption peaks. Whereas for the consumers, they should save more energy.

There is no doubt that smart meters are an indispensable part of the realization of Smart Grids because they are crucial to engage consumers to participate. In the French case, the smart meter Linky could make possible the location of capabilities of load shedding and the certification of their use. Moreover, the generalization of Linky should reduce by two thirds the technical losses and fraud, and by one third the small interventions on site [12].

However, apart from sometimes the consumers’ difficulty to accept these new meters, the financial problem with the installation of these meters seems to be very delicate. Indeed, to achieve the objective of the directive, which is to have a share of 80% of communicating meters by 2020, there is a need to spend 40 billion euros at European level. To the scale of the France, this represents an investment of 4.3 billion euros, so this gives us an idea of the
financial magnitude [12]. However, it is interesting to know that beyond a 58% share, the surplus generated by a smart meter gets less than its marginal cost (supposing that each smart meter has an average cost of 250 euros), which would mean that the investment is not optimal from a purely economic point of view [14].

Then a fundamental question should be asked: who should be responsible for the investment?

In general, the metering service is an activity managed by the distribution network operators (DNOs) in Europe. (Exceptions can exist; we will see a little further some examples.) Thus, it is to the DNOs to achieve investments for the replacement, operation and maintenance of the meters. The allocation of costs is decided by the regulator [19]. However, regardless of the management mode, it is to be known that it is always final consumers who pay the investment, in a direct or indirect way. Therefore, consumers will experience an increase in the electricity price.

In Germany, the situation is different. Indeed, there is a considerable number of small suppliers who occupy a large share of the market. It results in a loss of high efficiency at the time of replacement of meters: suppliers lack incentives to offer effective demand management services to their consumers, which is a pity since the potential profits, thanks to the implementation of smart metering technology, seem to be promising for suppliers [19]. This loss of efficiency could be worse if Germany had an operator like ISO (independent system operator) who does not own the networks. However, this option is not excluded today, because the adoption of an ISO is discussed in the country, arguing that it would be well suited to a policy favoring the integration of renewable energy sources.

In the United Kingdom, it seems that the emphasis is mainly put on better information of consumers, rather than real programs of demand side management driven by providers, which could induce changes in consumer behavior. This fact makes the implementation of smart metering not effective. The Consultation Paper of Ofgem said that with the innovation of the metering system, the achievable potential of energy efficiency through the spreading of smart meters should not exceed 1%, i.e. 3.2 TWh per year on average. While normally, dynamic pricing solutions can provide a much higher efficiency (it depends on the methods of pricing and the remote piloting of the load, but the gain in general is at least 5.3% and might even be much higher) [19].

Thus, we have seen that the change in the metering system is a complex problem. Obviously, there are financial challenges, but there are also challenges at the level of the organization of the electricity market. In addition, we must decide the priority of the functions performed by the new meters in order to reach the expected efficiency gains. Besides that, there is also the problem of acceptance of smart metering for consumers. They may find that
the new meters are complicated to use or even have a risk of violation of their privacy; this is what happened in some U.S. States for example.

If Europe or the United States hurry to implement smart meters nowadays, it is because on the one hand they are required for Smart Grids, and on the other hand, they are relatively simple to manufacture. Moreover, by involving large-scale investments, they are also seen as economic tools, particularly after the 2007 crisis. There is therefore a danger of rushing in the so-called intelligent components without worrying enough about the risks that may exist, or about the direction in which the electrical networks must develop. This could also be the case for other areas of intelligent networks.

GDF Suez is not only an electricity supplier, but also active in smart metering research and installations. However, the branch Tractebel Engineering France is not specialized in these fields, so less concerned by this liberalized energy market aspect of smart grid.
IV. A request for a better functioning of the electrical grid

IV.1. Looking for a better quality and reliability of the electrical grid’s operation

Historically, power reliability was mainly achieved by a margin of generation capacity, generators in power plants have a high power per unit, and the power flow was remaining unidirectional, i.e. from producers to consumers. Because of various reasons explained previously, the operation of electricity networks will look less and less to this classical description.

The opening of the electricity market posed a great challenge, the classical system was no longer suitable to the possible situations, and new networks were not ready neither when the famous 'black-outs' were held. Moreover, nowadays, we talk more and more about green energy or even about the electric vehicles; this could make management more complicated. Therefore, among all the criteria that smart electrical grids have to complete, the priority remains to make networks reliable again, i.e. to permanently satisfy the balance of production and consumption with more constraints, and even more effective possibly later.

This better functioning aspect of smart grid could be very interesting for Tractebel Engineering, especially the pole HEM, since HEM mainly studies electrical and mechanical aspects of different hydro plant projects. Their work covers the power plant itself, but also the electrical substations and electricity transmission lines.

IV.1.1. Greater speed of communication

In order to manage better electricity networks, a greater speed of communication between the various systems is essential. It is also one of the important features of Smart Grids.
Network operators want to gain a better understanding of operating conditions and be more able to manage rapidly what actually happens in the electrical system. As the electric network is very complex and dynamic, real-time and detailed information are essential to effectively manage such a system. This is why widely distributed sensors, microprocessors and automated control units are required, so that smart grids will be coordinated and considered as a whole system.

We must not forget that ideally, control centers must interact in real-time, not only with the sensors, equipment protection and control in electrical substations, but also with customers who can provide sufficient consumer flexibility or even production too, in order to contribute to the balancing of networks’ production and consumption. This is clearly what differs from traditional networks [8]. Indeed, with the increasing penetration of intermittent energy sources, there is a need for the interfacing of new resources of production, storage and customers who are willing to better synchronize their energy demand.

Thus, the difficulty of rapid communication between different parts of the network is partly due to the fact that there may be some very large volumes of data, which are potentially provided by every consumer (who can be active, i.e. he can change his behavior depending on the electricity price). And the system should be able to make decisions fast and adequate on the basis of these data.

On the other hand, to prevent "black-outs" like those of 2003 in the United States or 2004 in Europe, the grid must be firstly capable to isolate sections of the grid experiencing failures, which requires extremely fast protection. And secondly, it should manage to remote control the reconfiguration of certain network sections, or to stop certain equipment, according to the incurred incidents [8]. It comes here to implement some intelligent protection, control or automation equipment in the electrical substations.

If technologies in the crucial transmission substations tend to become more and more digital, there's still a work to do at the distribution level, in order to allow a two-way interaction with new users who may become micro producers. This requires control technologies at the level of the production and consumption resources.

There are lots of technologies that are used in the communication of Smart Grids, and the architecture is quite complex. A table that synthesizes a bit more information architecture of Smart Grids is given below, with a brief description of some key technologies in the system.
IV.1.1.1. Information system architecture for Smart Grids

In the current information system of electrical networks, we can distinguish three subsystems:

1. EMS or Energy Management System,
2. DMS or Distribution Management System,
3. WAMS or Wide Area Measurement System.

Each of these 3 systems includes some subsystems too. We can classify them in the table below:

<table>
<thead>
<tr>
<th>Energy Management System (EMS)</th>
<th>Distribution Management System (DMS)</th>
<th>Wide Area Measurement System (WAMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCADA (Supervisory Control And Data Acquisition)</td>
<td>DAS (Distribution Automation System)</td>
<td>PMU (Phasor Measurement unit)</td>
</tr>
<tr>
<td>AGC (Automatic Gain Control)</td>
<td>GIS (Geographic Information System)</td>
<td>Etc.</td>
</tr>
<tr>
<td>State estimation</td>
<td>DSM (Demand Side Management)</td>
<td>Etc.</td>
</tr>
</tbody>
</table>

Etc.

Here, we classify SCADA as a subsystem of the EMS system. Sometimes in literature, we also find the term "EMS/SCADA", in this case, EMS means the group of functions other than those performed by SCADA.

- **RTU**

RTU (Remote Terminal Unit) is an electronic device controlled by a microprocessor, which can be an interface between the physical world and a control system or SCADA (control and data acquisition) by transmitting telemetry data to a master system, and by using messages from the master control system to the connected objects [20]. The main problem of
RTU for Smart Grids is that its data acquisition frequency is low, therefore this prevents access to the electrical network’s information in real time. In addition, different RTU units have no synchronized clock with each other, which makes that acquired data are not synchronized [21].

SCADA is a large scale remote management system that can process in real time a large number of telemetry and remotely control some technical installations. It is widely deployed today around the world, in the electricity sector. As it is based on the use of the RTUs, its main disadvantage to fit Smart Grids is that its data collection is too slow (in the range of 0.1 s) for real-time applications.

- **PMU**

Phasor Measurement Unit (PMU) is a device which measures the electrical waves on an electrical network, using a common clock for synchronization. Time synchronization is able to synchronize several measuring points remotely in real time over the network. PMU is considered to be one of the most important measuring devices in the future of power systems [22]. It can be a dedicated device as well as a feature incorporated in another device [23]. It has the advantage of being more precise about the measures and has a greater acquisition frequency compared to RTU.

Thus, WAMS, which is also a large scale remote management system, by using PMUs, has a shorter response time (in the range of milliseconds) compared to SCADA, and temporal synchronization is also provided by the GPS through satellites. It performs an improved analysis of electrical networks and detects any instability by integrating the phase measurement [9]. However, even if it is technically well suited to Smart Grids, it implies the construction of specified infrastructure, which means a significant investment [21].

- **Information system architecture**

Information system architecture for Smart Grids is composed of three layers:

- Infrastructure layer, including power grid devices and communication network;
- Supporting platform layer, including sensing and measurement, data and storage, analytics and decision, control and execution;
- Application layer, including generation-side, grid-side and demand-side applications.
We can synthesize the technologies and standards used for different layers in the following figures.

Figure 1  Information system architecture for Smart Grids

Figure 2  Architecture of application layer
Figure 3 Architecture of supporting platform layer
Figure 4 Architecture of infrastructure layer
We can see in the figure 3 that there is a standard dedicated to electrical substations, it is IEC 61850. This standard is very interesting for Tractebel Engineering, because on the one hand, it aims the interoperability of different equipment suppliers for a smarter substation; and on the other hand, it also will possibly become an important norm for hydro power plant in the future. Further details are explained at chapter VII.

**IV.1.1.2. Communication technologies**

As the large scale measures and control techniques are developed and deployed to make the electric system stronger, the role of communication network becomes very important. The advanced communication infrastructure must allow a greater observability of the system and a globally optimal control. In this context, there is a growing trend in the use of the wide area measurement system (WAMS) with units of measure such as PMU (Phase Measurement Unit). However, the large amount of data remains to be transferred via communication networks, to control centers, where the estimation of real-time status, protections, or control decisions are carried out. The volume and the frequency of these data transfers, and the request of doing it in real time, demand a significant bandwidth and appropriate delay characteristics, in order to ensure the proper operation functioning. [24].

There are many technological possibilities to achieve the communication infrastructure, with its advantages and its disadvantages for each. PLC (power line communication) seems to be a mature communication technology, but this is not the only option. Other possibilities such as wireless or optical fiber exist. Being responsible for power line designing aspect in several projects, it's good for Tractebel Engineering to weigh the advantages and drawbacks of these technologies here.

**IV.1.1.2.1. Power line communication**

Power line communication, or PLC, is based on the principle of simultaneous transmission of data and electricity on existing power lines, data are in the form of a signal with higher frequency compared to the typical frequency of AC power transmission, which is 50 or 60 Hz.

There are generally two categories of PLC: narrowband and broadband. For narrowband communication, there are different ranges of frequencies according to the governments. According to the European standard, it must operate in the frequency range of 9 to 140 kHz with a maximum of 128 kbps as data rate, while the American standard of the Federal
Communication Commission allows the use of the frequency spectrum up to 500 kHz, providing 576 kbps as data rate.

While for broadband communication, it must operate in the frequency range of 500 kHz to 30 MHz, and a high transmission speed, i.e. 100 Mbps at least, is expected [1]. Transformers, due to their high inductance, act as low-pass filters; the high frequencies are therefore filtered. Consequently, for broadband communication, capacitances are required to be attached to transformers so that high frequencies can pass.

The advantage of the power line communication is that power lines are already installed everywhere, it doesn’t need to redo an entire infrastructure, and this is especially true for rural areas where there is no communication infrastructure. In addition, this communication network can be easily profitable, because it uses existing power lines. PLC, until now, is the most widespread communication for conventional electrical grids.

However, PLC has its own drawbacks especially due to the fact that the electrical grid is not designed for high-frequency transport. The cables are not shielded; making that the high frequency signal sees much of its energy dissipate in the form of radio wave. In addition, lightings, electric motors and the radio signals are all potential sources of noise. Thus, a significant noise could result in high error rate for the data transmission [1].

There is another drawback; it’s the problem with the open circuit. Indeed, it sometimes happens that the switches in some places in the electrical grids become open. Therefore, the communication is interrupted at these sites, which can be annoying.

Like other methods of communication, there is always a need of thinking about the information security problem. With PLC, due to the nature of the current cables, signals can be received by other radio receivers. Therefore, the encryption of data is essential.

**IV.1.1.2.2. Optical networks**

This communication infrastructure provides high data rates. In addition, it is insensitive to electromagnetic interference or interference with radio frequencies. It is considered as an ideal communication support for high-voltage lines. Thus, the optical fiber has become a trend today for communication of Smart Grids. It is possible to install it on pylons. This technology is mainly used for transmission grids, between the substations and the control center for example, and it is still rare in distribution grids.
Sometimes, optical networks appear to be necessary, it is the case of standard 61850 aiming the automation of electrical substations. Indeed, according to this standard, messages between intelligent electronic devices must be sent every 4 ms, which requires a great speed.

However, the installation of new optical cables is expensive and requires a lot of buildings that are time consuming.

**IV.1.2.3. Wireless communication**

Among all the wireless technologies, WiMAX (Worldwide Interoperability for Microwave Access) and WMN (wireless mesh networks) are two technologies to mention in the realization of Smart Grids. Other technologies such as Zigbee also exist.

- WiMAX can cover an area of radius going from 5 km to 50 km and provides a great data rate (a few tens of Mbit/s [25]) that can goes to 100 Mbit/s [1]. It has the advantage of working on a licensed wireless spectrum: 2-11 GHz. However, it has the disadvantage of not being as secure as wired communication.

  WiMAX is part of the concept of the cellular network communication. Other technologies such as GSM, 2G, 3G are also part of this family. More generally, these technologies have a cost advantage, and are already fairly widespread. However, in some important cases, we need a continuous availability, which is not assured, since there could be congestion problems when services are too solicited [26].

- Wireless mesh network is a choice selected by some operators in the United States. This technology is to use a group of nodes so that each node can act as a router, and there is possibility of incorporating new nodes. Thus, if a node stops working, signals will still be able to borrow another path, so there is a 'self-healing' character with this structure.

  Its advantage is that it can be deployed easily, without the need of sophisticated planning. His redundancy due to its structure offers a fairly high degree of autonomy. However, it experiences a high latency, because in the case of Smart Grids, smart meters act as relay nodes to route messages to other meters. In addition, the fact that it uses unlicensed radio frequencies is a disadvantage because it can interfere with other communication devices [1]. Finally, the density of meters may be insufficient to cover the entire communication network [26].
• ZigBee is a technology which is rather appropriate for the field of residential systems according to U.S. National Institute for Standards and Technology. It can provide communication between smart meters or appliances. Advantages include simplicity, mobility and relatively low cost. But its limited memory or the risks of interference are constraints for the implementation [26].

In general, wired communication such as the PLC or the optical fiber technologies are more expensive, but they increase the capacity, reliability and security of communication, while wireless technologies often have cost advantage, but their bandwidths are more limited, and reliability or safety problems exist.

IV.1.2. Interoperability

When intelligent electrical appliances are connected to the communication networks, there is a need to communicate information at the level of electrical substations, but also to a higher level. In the past, as there were several protocols in this field, this posed a problem of adaptation between different protocols. Thus, interoperability could be sought, both by users and providers.

International Electrotechnical Commission or the IEC is the international organization responsible for standardization on fields of electricity, electronics and related techniques [27].

In principle, the IEC remains the principal place of standards in order to avoid duplication of standards. And France enjoys a strong representation in the committees of the IEC which has many influences in the standardization of Smart Grids. Among the prior actions in term of standardization at IEC, we can find especially:

• Accelerate the underway processes,
• Harmonize energy measures and their control by enforceable rules
• Formalize rules of protection and confidentiality of personal data.

In 1995, a group of project IEC began working on the development of the IEC 61850 standard which includes the automation of electrical substations. Under this standard, interoperability plays an important role. As a result, users can expect a new degree of freedom while manufacturers may have a margin of creativity when they need to develop new systems for example [28].
Here we open a small parenthesis: with regard to Smart Grids, the IEC created in 2008 a strategic group dealing with this subject. It established a road map and a list of hundreds of IEC standards currently applicable, including IEC 61970 (CIM), IEC 61850 (automation of substations) and IEC/TS 62351 (security). On the side of the United States, NIST (National Institute of Standards and Technology) also established a framework and a roadmap for Smart Grids interoperability standards. By working closely with NIST, the IEEE (Institute of Electrical and Electronics Engineers) has developed even a roadmap for standards, and a framework for testing/certifications of compliance [29].

If we are talking about standards, it is precisely because they are crucial if we want that equipment of different types or uses in various entities of the network connection can be integrated. Here, the various entities can refer for example to conventional consumers, electric vehicles, renewable energy parks, etc.

Moreover, from an economic point of view, standards are also essential to ensure operators a return on technology investment. Indeed, if we put in place a set of standards that can ensure interoperability within Smart Grids, this would give confidence and motivation to the market to invest in new applications and new technologies.

However, we should be aware that if standards are too late, it means that the costs of transition to the new standard will be too big, and that new technologies will have trouble to be adopted. On the other hand, it may as well as the standards arrive too early, i.e. premature, so that future technologies are not yet ready. Thus, apart from the normative or technological difficulties, timing also plays a decisive role. In addition, it is often the case for other devices related to Smart Grids: timing is an important factor and must be taken into account. For example, we can think about the problem of electric vehicles. Indeed, the democratization of electric vehicles will pose a great challenge to the stability of power grids.

For more details, the second part of this thesis is devoted to the study of the IEC 61850 standard.

**IV.1.2.1. Electrical substations**

As defined by the International Electrotechnical Commission, an electrical substation is the "part of an electrical grid, consisting primarily of the ends of the transmission or distribution lines, the electrical equipment, the buildings, and possibly, the transformers, located in the same place."
In principle, an electrical substation serves as the transmission and distribution node of electricity. It allows to raise the voltage power for transmission, then to go down for distribution, in order to be consumed, whether by individual users or manufacturers.

Substation is a central point in the Smart Grids system because, as mentioned in the previous section, if we manage to collect effectively a sufficient amount of information such as currents, voltages and frequencies in all substations of a system, then we can have an accurate estimate of the system state and react properly against possible disruptions. This of course assumes the establishment of modern sensors and other intelligent electrical devices, which must be interconnected in the so-called digital substations [28].

Among the expectations of digital substations, we hope that thanks to automation, they will perform the data acquisition, remote communication, supervisory control, protection, detection and evaluation of defects [9]. They could also allow the preventive maintenance and increase life cycle of transformers [28]. These substations will be modular, so that they can be adapted to the needs of the system, and remain open to new equipment.

During the substations automation, it’s very important to remain consistent with the standard of communication IEC 61850 because this would allow interoperability with other consistent and similar products.

Here, it is important to distinguish between interchangeability and interoperability. According to IEC 61850-1 definition, interchangeability is the possibility of replacing a device provided by a manufacturer of another one provided by another manufacturer, without making any changes to the other elements of the system. While interoperability is the ability of two or more equipment from the same supplier, or from different suppliers, to exchange information and to use that information for the performance of specified functions.

Thus, IEC 61850 aims firstly interoperability, and not interchangeability. The latter could be, of course, one more advantage. In some works, it happens that people talk about “plug and play” as if it were a feature of interoperability of automated substations; however this is mainly about interchangeability in this case. Therefore, we should be aware that the concept of interoperability can be misinterpreted.

IV.1.3. Cyber-security

In the previous section, we talked about the interoperability of Smart Grids’ equipment. In reality, this interoperability can mean new difficulties. In the past, infrastructure did not have a role as important as today in control systems of electrical grids,
and new connection points required for future networks may also become targets of cyber-attacks [28].

Historically, even if it is in the US definition of Smart Grids that we find the meaning of the term “cyber-security”, nowadays, everyone seems to agree with the fact that this will constitute an essential application for future electrical systems.

Indeed, designed to provide a real-time communication between different parties, including smart meters in homes or intelligent equipment for industrial consumers, Smart Grids have a real risk of being, with its technologies, exploited for malicious purposes. For example, we can imagine the possibility of knowing or even remotely controlling the status of the customers’ consumption. It is certainly an advantage for the suppliers or grid operators, but this raises also the important security issues.

Being able to control the switches with Smart Grids in the future could already create a huge security challenge that we are not used to dealing with. We can imagine that the cyber-attacker may as well be a terrorist organization as a hostile country, passing by environmental or anti-Government activists. Power grid can remain as an ideal option to attack a country because when the electricity stops, everything stops. In addition, the fact that the grids are interconnected makes this task even more difficult. Indeed, if there is a fault somewhere, there is a chance of inducing other faults. This is why Smart Grids must be able to manage local faults and limit them, to prevent "blackout" on a large scale.

With regard to intelligent decision about Smart Grids, there are also security risks. In general, data from devices connected to the network should be delivered to controllers that are most probably located in the operator control centers. The data must be processed before being communicated to other devices. This is accomplished by communication networks and the IT layer. In other words, it is necessary for the data to be transmitted in a reliable and secure manner during this whole process. Another way of communication exists too, it is direct communication between devices. It goes the same for interoperability and security in this case.

As communication is ubiquitous between systems of different natures, we must be aware that possible "cyber-attacks" on electrical networks can lead much more devastating consequences than classic cyber-attacks on the internet, since it is attacking the physical world. There have already been examples such as the "Stuxnet" computer virus attacking Siemens control systems.

To cope with the challenges of cyber-security, in Europe, there is a committee called «Smart Grid Expert Group 2» who studies on the regulation for the cyber-security of the Smart Grids [30]. Its main concerns are somewhat nuanced compared to the United States.
because emphasis is placed on energy theft and the privacy of consumers, while in the United States, NIST publishes guidelines that deal with concerns on energy theft and cyber-terrorism. However, the dangers may still exist. These days, Smart Grids sometimes become an economic or environmental necessity and therefore the issue of cyber-security may not be treated enough as a priority [31].

IV.2. Research of electrical grids efficiency

To meet energy needs, a 1 GW power plant per week must be built in the world and this rate should be kept for 20 years, according to the International Energy Agency’s forecast [5]. We see the scale of this power plant construction wave and the potential energy and environmental impacts this could have. There are of course solutions such as wind turbines or photovoltaic, however, it should be noted that the development and integration of green energy sources represent only a part of the solutions. In fact, it is shown that if we seek to use the current energy in a more effective manner, the potential reduction of CO2 emissions is already larger than all the other options that exist [32]. In other words, searching for better electrical grids efficiency must be a priority. However, according to a study by the United Nations, from a financial point of view, if 119 billion dollars are invested in clean energy worldwide in 2008, only 1.8 billion dollars was spent on improving energy efficiency [33].

The lack of knowledge of consumers and public authorities about the energy efficient equipment is only one obstacle. Another real impediment is the lack of incentives: indeed, if we take the example of an industrial consumer, a purchasing manager would not interest to spend more of its budget to effective equipment if all the economies go to the service that pays for electricity [5]. And for companies that are working in the energy sector, investing in renewable energy seems to be more promising economically.

We can distinguish two possibilities to increase the efficiency.

1. The first one is to reduce the loss before consumption.

2. The second one is to do demand-side management of electricity.

The first possibility exists because of the fact that nowadays, the way electricity is produced, transported, and used is not effective enough. In some cases, solutions such as HVDC technology can reduce this inefficiency. This aspect is all the more important as the large wind farms or hydro plants are sometimes located far away from consumers and ask a long-distance electricity transmission.
High voltage direct current or HVDC is a technology that converts alternating current of generators to direct current for transmission, before converting it back to alternative for consumers. This technology is ideal for transporting power for places with difficult environment (for example submarine) or for long distances with low losses. Because alternating current has the disadvantage of producing reactive power in the cable and causes losses of active power, whereas DC does not have this problem. For submarine transmission, reactive power produced in the cable would be too large if it was AC. And compensation devices are possible but expensive. Thus, high voltage direct current is widely used for submarine cases [34]. Moreover, as said before, since power plants can be located far away, HVDC can be a good choice for transmission.

Among the achievements using HVDC technology, the overhead line of the Inga-Shaba project, in Democratic Republic of Congo with a distance of 1700 km, was the longest in the world. This project was completed in 1982 with a cost of 900 million dollars [35].

The longest submarine cable is used in the project of NorNed, with a distance of 580km, linking Norway and the Netherlands [36].

Project Itaipu in Brazil, put into service in 1986, had the highest voltage level for more than twenty years, i.e. +/-600 kV.

In the case of the Xiangjiaba dam in China, a 2000 km transmission distance was set up, for transporting its energy mainly to Shanghai, and using ultra high voltage direct current, i.e. +/-800 kV [9]. For the moment, it is the world record in terms of the voltage level and the transmission distance. The Rio Madeira project, under construction in Brazil, should have a distance of transmission of 2500 km [37].

However, HVDC requires more complex devices compared to the classical solution of alternative current (for example, more sophisticated for converters or circuit breakers), this means both a technological challenge and a non-negligible cost.

For the second possibility, i.e. demand-side management, it is about working in a smarter way. For conventional electrical grids, when there is an increase in demand, this means an increase of use of generators in reserve, otherwise the load shedding. This approach has not only the inconvenience of being costly since the energy produced by generators in reserve is generally more expensive than that produced by generators operating continuously, moreover, this may have the disadvantage somewhat on the use of renewable energy. Thus, rather than follow the demand of electricity, it is preferable to work while remaining intelligent, i.e., to adopt a more holistic view of grids, and depending on availability of generators, to encourage consumers to change their habits and behaviors [38]. Although the principle is simple to understand, the demand-side management is very complex and involves
many technologies (such as energy storage techniques, communication, etc.) and concepts (such as the micro-grid or very short-term electricity market). Some important concepts like "micro-grid" will be defined and dealt with in the following chapter.

V. To achieve the environmental objectives

V.1. Generalities

There are environmental objectives at European or national level that have impacts on the development of Smart Grids. Here are some numbers that have already been mentioned in chapter II.

By adopting, in 2009, the objectives of the 'three 20 targets' (or ‘20-20-20 targets’) [6], the countries of the European Union engaged in a collective effort to achieve by 2020 the following goals:

- To reduce emissions of greenhouse gases by 20% relative to 1990 by 2020,
- To increase energy efficiency to save 20% of energy consumption relative to 1990 by 2020
- To reach 20% of renewable energy in the total energy consumption in the EU by 2020.

Regarding France, the objectives to be achieved are as follows [6]:

- The electricity produced by renewable energy (hydraulic not included) should represent 23% of French consumption in 2025, knowing that it is 2.8% today.
- Electricity from nuclear power should represent a 50% share in 2025, knowing that it is 74% today.
- The share of thermal electricity is expected to decrease from 11% to 2.8% by 2025. (The share of hydropower should nearly be constant, around 10%)

Today, coal is only used for the electricity production during peak periods in France, and this represents a little more than 13 TWh in 2011, that’s roughly 2.5% of the electricity produced in the country and 30% of the non-nuclear thermal electricity [39]. However, coal power plants are still the most widespread ones in the world and provide approximately 40% of world’s electricity production. This fact makes electricity production remains the largest contributor to the increase in CO2 emissions [5].
It is true that the growth rate of the electricity production from renewable energy is very high in recent years; however the share of the contribution of green energy is still low in the global energy mix. Renewable energy such as wind or photovoltaic is often intermittent and variable, which poses additional challenges to electrical grids. Another disadvantage of these new energy sources is their availability, because it may be possible that these sources of production are unavailable during consumption peaks, which highlights the importance of the energy storage development which would provide a greater flexibility in the grids management.

A broad definition of new energy sources includes ‘dispatchable energy’ and ‘non-dispatchable energy’. In general, hydro, biomass and geothermal energy belong to dispatchable energy and wind, solar or tidal energy are considered to be non-dispatchable. The argument of this division is that the production of dispatchable energy is controllable, while time or the amount of wind energy, for example, is not controllable. As a consequence, the management of dispatchable energy integration to the grid has no significant difference compared to fossil fuels, while non-dispatchable energy can have effects on the stability of power systems [21].

- **Hydro power**

Hydroelectric energy is obtained by conversion of hydraulic energy from different natural water flows into electricity. By using the turbines, the kinetic energy of the falling water is transformed into mechanical energy. Then by using alternators, this energy is transformed into electrical energy. In 2011, the hydropower represents approximately 16.2% of world electricity production [40].

Hydroelectric energy is traditionally the renewable energy source in the electricity sector and according to the International Energy Agency or IEA, this will continue to be the case for the next 20 years. An essential advantage of hydro power is its storage capacity with the transfer of energy by pumping. This method remains for now the only way to the efficient energy storage in large quantity. That’s why Tractebel Engineering’s activity can be interesting again in this new context of smart grid.

- **Wind and solar photovoltaic energy**

A wind turbine converts the kinetic energy of the wind into mechanical energy, and afterwards into electrical energy.
Regardless of the expected size of the renewable energy sector, the production of wind energy will surely play a very important role in the future. In some countries such as Germany, wind turbines already have an important role in the electricity production. However, if there is still room for new wind parks in some regions, in general, it becomes more and more difficult to find new places where it is profitable to build parks. Thus, with technological advances, the potential for off-shore wind farm installations becomes increasingly large [41].

The photovoltaic energy is electricity generated by photoelectric effect, from the solar radiation, by using semiconductors.

The development of photovoltaic production is limited by the fact that the generation is intermittent and there is often a time lag between electricity production and the increase of actual consumption. Like any other intermittent and variable energy, a massive deployment of photovoltaic systems can complicate the balance between production and consumption, if electrical grids are not yet well adapted. It is shown that the energy storage batteries can be used to store the power produced at noon in long term so that they provide a complementary feeding at night, and super capacitors can be units of energy storage for faster answers to the consumption needs [42].

In general, whatever we choose between wind turbines and photovoltaic power plants, we are facing intermittent production. Thus, a system of local energy management must be developed in order to allow:

- The management of intermittent and renewable energy resources
- The quality of electrical power
- The management of energy level
- The protection of power system
- The provision of ancillary services of grids [42]

And this is also the case in general for other renewable energy.

- Tidal energy

If the energy produced is not necessarily synchronized with the consumption, nevertheless it has the advantage of being totally predictable. There is also a possible reversibility of energy with pumping system, just like in the hydroelectric plants [43]. Today there are some projects of 1MW using tidal energy in the Great Britain.
V.2. Constraints of renewable energy

V.2.1. Intermittent energy

Certaines énergies renouvelables, typiquement l’éolien et le solaire, sont directement corrélées aux phénomènes météorologiques. En conséquence, cela peut induire une fluctuation de la capacité de production et donc une source d’instabilité dans les réseaux électriques. La production centralisée classique, c’est-à-dire avec les centrales nucléaires, thermiques, hydroélectriques, ont une plus grande flexibilité vis-à-vis de la demande, puisque l’énergie peut y être stockée sous forme de retenue d’eau, d’énergie fossile, alors que les énergies renouvelables ne peuvent pas adapter leurs productions à la demande des consommateurs [8].

With a more and more important participation of renewable energy in electrical grids, it would be good to be able to control their intermittences. A possible solution is to make grids smarter so that the demand can be flexible depending on the production, for example by using notions such as the micro-grids which try to solve the problem locally, instead of systematically asking help from the main electrical grid (see section V.2.2). Another solution is to make progress in the electricity storage so that it would offset the intermittent character of energy in question [12]. We should be aware that independently selected for intermittent energy solutions, keep it to improve conventional power steering and control systems because they require a faster response to network fluctuations. Be aware that regardless of the chosen solutions for intermittent energy sources, it still remains to improve the control systems and the management of conventional power plants because they must have a faster response vis-à-vis fluctuations networks.

V.2.1.1. Wind farm

With regard to the integration into the grids, wind turbines have two problems to solve. The first one is the problem of the energy quality, since the wind speed variation can cause fluctuations in the frequency and the voltage in the normal regime of operation. The second one is the problem linked to the continuity of energy production, due to the wind instability, because the turbines will stop when the wind is too weak or too strong.

The first above mentioned problem is solved now by using electronic devices such as converters, inverters capacitors and technologies such as SVC (static var compensator), STATCOM (static synchronous compensator).
To resolve the second problem, there are two main ideas:

1. To achieve a stable power at the output, there must be a prediction of the production of the wind farm in advance, associated with the measured load information in real-time. Then, a system must be able to handle the energy storage and to do system planning in real time. In reality, an important reserve is often kept to deal with the variability of wind generation, but this reduces in other words the benefit from the exploitation of wind energy. In order to get the most of green energy, estimation of the power produced by the wind farm from a few hours up to a few days are very important [44]. However, this solution requires the implementation of a number of devices for energy storage and support systems, therefore, the cost is high.

2. The second idea is to reduce the load when there is a decrease in the production of wind turbines, through a system of real-time control for the balance of the grids load and wind production. This idea can reduce the size of the storage device, which reduces the cost of construction.

Regardless of the adopted here idea, it is about to be able to collect data in real time, therefore it needs the support of the information system for Smart Grids [21].

V.2.1.2. Energy storage

The production/consumption balance must be respected at all moments; any imbalance will result in a frequency deviation in the interconnected grids. Energy storage is a major issue in the context where large amounts of intermittent energy sources are added to the mix of power supply.

Today, the main forms of energy storage can be divided into storage in mechanical energy (such as pumping, compressed air energy storage or storage by the flywheel), storage in electrochemical energy (such as sodium-sulfur, lead-acid and nickel-cadmium batteries), and storage in electromagnetic energy (using superconductors of super capacitors) [45].

There are two important points concerning the energy storage, the first is obviously the storage capacity, high capacity is usually preferable. The second point is the speed and the efficiency of the conversion: indeed, technologies permitting fast and efficient conversion mean a shorter response time to participate in the grids balancing [14].

Electrical energy storage applications include energy storage for households, community, and the relief of the system. The typical capacity of storage for household
equipment is in the range of kW, with 220 V as the access line voltage. The capacity of community storage is usually around tens of kW, with 380 V as access voltage. The ability of emergency power is typically from a few tens to hundreds of kW, it can be connected to 380V line, but sometimes by voltage rise, the system can be connected to branches of 10 kV. (These figures are just indicative) When there is a network failure, the energy storage system should operate independently.

The typical capacity of the energy storage system at the level of the substation is at least in the range of MW, it is supposed to significantly improve the stability and reliability of the grids and reduce the difference between the peaks and troughs of the load curve.

At the production level, a typical energy storage system is at least a few megawatts and can reach several hundreds of megawatts. Most often, it is associated with large scale wind farms or photovoltaic production. It is supposed to improve the integration of renewable energy [46].

According to the different types of storage, the powers and energies that can be stored are obviously different, which leads to various uses. In the following table, we summarize some interesting storage technologies.
Table 2 Comparison of different energy storage technologies [45] [47]

<table>
<thead>
<tr>
<th>Storage type</th>
<th>Typical power</th>
<th>Duration</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Storage in mechanical energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pumped hydro</td>
<td>100~2000 MW</td>
<td>4~10 h</td>
<td>Daily load regulation, frequency control, emergency supply</td>
</tr>
<tr>
<td>CAES or compressed air energy storage</td>
<td>100~300 MW</td>
<td>6~20 h</td>
<td>Peaks of consumption, emergency supply</td>
</tr>
<tr>
<td>Micro CAES</td>
<td>10~50 MW</td>
<td>1~4 h</td>
<td>Peaks of consumption, emergency supply</td>
</tr>
<tr>
<td>High power fly wheels</td>
<td>5 kW~1.5 MW</td>
<td>15 s ~ 15 min</td>
<td>Peaks of consumption, frequency control, Uninterruptible power supply (UPS), power quality, distribution and transmission systems stability</td>
</tr>
<tr>
<td><strong>Storage in electromagnetic energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High power super capacitances</td>
<td>10 kW ~ 1 MW</td>
<td>5 s ~ 5 min</td>
<td>Uninterruptible power supply (UPS), power quality, distribution and transmission systems stability</td>
</tr>
<tr>
<td>Super capacitance</td>
<td>1~100 kW</td>
<td>1s ~ 1 min</td>
<td>Power quality, distribution and transmission systems stability</td>
</tr>
<tr>
<td><strong>Storage in electrochemical energy</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced lead acid battery</td>
<td>1 kW~50 MW</td>
<td>1 min~3h</td>
<td>Power quality, frequency control, emergency supply, UPS</td>
</tr>
<tr>
<td>NaS Battery</td>
<td>100 kW~several MW</td>
<td>mins~hours</td>
<td>Divers applications</td>
</tr>
<tr>
<td>Flow batteries</td>
<td>100 kW~several tens of MW</td>
<td>1~20 h</td>
<td>Power quality, emergency supply, peaks of consumption, integration of renewable energy</td>
</tr>
</tbody>
</table>
Compressed air energy storage is a technology that consists in compressing air into a tank, and when there is a need, it converts energy through turbines during the discharge of air, in order to generate electricity.

High power fly wheels energy storage is to store kinetic energy in the rotating fly wheel and this rotational energy is converted into electrical energy via a motor/generator. This technology is simple to manage, and has the potential to have a power relatively large but only for short periods, that is why it can be used to improve the energy quality [48].

The pumped hydro is a storage technique of electrical energy that involves pumping water to store in the reservoirs when electricity demand is low, so the energy is stored as potential energy by this method. When demand is high, this energy is transformed into electricity through the turbine. From a viewpoint of delivered power or stored energy (see above table), it is still the most effective energy storage technique that exists nowadays. This is why, in the future, hydro power plants and Tractebel Engineering France with its big expertise in hydro power domain, will continue to play an essential role in the electrical grid.

With the development of electric vehicles, in the future, there is a possibility to intelligently manage their batteries in order to participate in the energy storage. Until today, with the integration of dispersed energies, the conventional way to keep the functioning of the electrical grids is the strengthening of weak power lines. However, this is expensive. Another method is therefore to develop more advanced management to drive distributed loads and generators. The batteries of electric vehicles can be seen both as loads or generators according to their modes of operation.

V.2.2. Distributed generation

With the liberalization of the market and environmental objectives, the distributed generation is expanding on electrical grids. This kind of generation is often characterized by small capacity (typically between 3 kW and 10 kW) facilities at low voltage levels. So far, small wind turbines or photovoltaic panels remain the main sources of distributed generation and these types of production can have a significant impact on the safety of the grids operation. If historically, grids have a one-way energy flow, i.e. from producers to consumers, distributed generation introduces two-way flows.

The main challenges are the following:

- Direct access of this generation to distribution grids can introduce disturbances to power quality, such as fluctuations in the voltage of the system, the harmonic pollution or the frequency deviation [49].
• It has an impact on the functioning of the protection equipment due to transits power or short-circuit current [2].
• The high degree of uncertainty of the generation, because of the nature of renewable energy, would make planning more difficult, which may reduce the reliability of the grids. On the other hand, if we consider this production only as a source of backup power, there are certainly fewer problems for planning but that translates into a loss of resources since distributed generation is not operating at maximum [49].
• Interaction between generation sites and regulation in real time already exist in traditional grids, but the number of control points is a few hundred whereas dispersed generation resources require tens of thousands of control points. This makes management more complex [8].

As the classical regulation system is not able to manage the dispersed energy generations which are hardly predictable and dispatchable, in order to avoid harmful consequences for grids, distribution operators may impose strict rules for new connections. But it is about to limit the rate of penetration of distributed generation [2]. Therefore, guarantee the safety of the grids (which is a priority) while trying to incorporate green energy as much as possible becomes a complicated problem to solve.

Currently, there is a lot of research trying to find innovative solutions for a growing integration of distributed generation. Some studies think about the location and the optimal size for decentralized production, others are trying to reduce the uncertainties of production and consumption. For example, in the previous part, we discussed energy storage technologies; these can help green energy to have a more stable production. Today, energy storage technologies are mainly limited to pumping water whose technological developments allow an increasingly fine and precise steering in response to energy fluctuations [8]. There are also studies on the structure of electrical grids, with the aim of encouraging the integration of dispersed generations (In urban areas, load density is high. Therefore, large quantities of energy are to be delivered over short distances. In this case, the authorized maximum current is often a main constraint. While in rural areas, there is often less energy to transport but the distances involved are big. Thus, the voltage drop becomes a significant constraint. That’s why we have different network structures). Finally, concepts such as "micro-grid" are much studied too.
V.2.2.1. Micro-grid

A micro-grid is a local grouping of electricity production, energy storage and loads, which are normally connected to a traditional main grid. However, this connection point with the main grid may be disconnected. The micro-grid can then operate independently [50].

The micro-grid is seen as the ideal solution to solve problems related to distributed generation. From a point of view of the main grid, the micro-grid is a load; from an internal point of view, the micro-grid sees itself as a complete power system.

One of the features of the micro-grid system is that it can operate in different modes, based on different circumstances. There are three main modes of operation [21]:

- **Connected mode to the main grid**: the micro-grid is integrated into the main power grid and there is exchange of power;
- **Independent or autonomous mode**: the micro-grid is integrated into the electrical grid, but there is almost no energy exchange;
- **Isolated mode**: the micro-grid is disconnected from the main grid and manages its operation independently.

In a micro-grid, every household ideally can be an actor of the grid by selling his production or by adapting his consumption depending on the load. The system managing the micro-grid of the neighborhood provides real-time load information that determines current sales and purchase prices based on the users subscriptions [51]. When consumption exceeds production, new means of production will be started in the micro-grid, or more energy can also be imported from the main power grid, and certain current consumption can be reduced or stopped. When production exceeds consumption, certain means of production are turned off, and the rest of energy will be stored or sold to the main grid.

The micro-grid is also considered as a potential solution for the management of electric vehicles that need to charge their batteries in an unpredictable manner. Indeed, if charging is firstly taken into account at the micro-grid level, then the problem can be primarily solved locally, this can avoid disturbances on the stability of the main grid.

However, there are several difficulties to ensure the proper functioning of the micro-grid. First, the resynchronization with the conventional grid is difficult. In order to let the electricity generated by the microarray be distributed on the main grid, parameters such as voltage, frequency or power must be controlled. Moreover, protection in different operating modes must be considered. For example, the overcurrent due to a fault in the micro-grid is often not large enough to trigger the conventional protection equipment [21]. In addition,
energy control and management system must be developed for each micro-grid. Finally, it requests obviously a considerable financial investment.
VI. Economic aspect

V.1. Motivations and dangers

The magnitude of the financial investment involved in the development of Smart Grids is non-negligible as we already mentioned some figures in chapter II. This market assessment varies greatly according to the parameters taken into account in the forecast. Gimelec, for example, gives a range of 12 to 50 billion euros per year by 2020, for the world market of Smart Grids [18]. According to IEA, International Energy Agency, by 2035, 70% of European investment in the energy sector will concern the electrical energy [14].

Investments in Smart Grids include both opportunities and dangers. For example, the deployment of smart meters becomes a tool in some way for the economic recovery. From now till 2020, investments in energy infrastructures will be around 1000 billion euros [12]. However, such amount of money becomes too colossal in the current economic context and the operators are already heavily indebted. It will therefore be necessary to establish priorities for investments. In addition, consumers will fear too large increase in their electricity price since they are the ones who will pay the investment, in a direct manner or not.

Indeed, saying that the competitive market may lead to a fall in prices does not necessarily apply to electricity, even if it was a desired outcome at the beginning of the reform of electricity market. The costs of investments necessarily have an impact on prices, but according to IEA, it is still possible to think that the bill paid by consumers is going to drop thanks to a reduction in consumption, since it is going to be managed more intelligently [14].

V.2. Regulations and investment incentives

Because of the uncertainties about the potential gains, actors may delay their investment and research, waiting for a decrease in risks. In addition, even though there is benefice, those who invest will not be the only beneficiaries, and this could discourage their investment. Indeed, for example, the investment made by the distribution grid operators can have positive effects for suppliers who will be able to fit better their strategies through the relevant data, for consumers who will control better their consumption, for local authorities who will benefit of Smart Grids to achieve national or European objectives [14].
On the other hand, consumers’ reactions are sometimes unpredictable; this is for example the case for smart meters. Consumers might find smart meters too complicated to use, or still fear a potential leak of privacy, and therefore refuse the installation of smart meters or even request refunds if it is already installed.

In summary, there are several categories of uncertainties that may prevent investments:

- The uncertainty about the benefits of new technologies and research,
- The uncertainty about the consumers behavior,
- The uncertainty about the way in which the benefits will be distributed or allocated [14].

Thus, the regulations have an important incentive role to avoid waiting games and doubts; they must guarantee the effectiveness of investments and minimize the risks. Even though these economic uncertainties concern more directly the main branch of GDF Suez than Tractebel, it is still good to know them. For instance, in the following chapters, we will analyze the feasibility of application of IEC 61850 to an existing project, but we should be aware of the actual lack of knowledge of investment cost for this eventual application.
VII. Presentation of standard IEC 61850

In the previous chapters, we have seen that among all the motivations, the better functioning of smart grid is probably the most important aspect for Tractebel Engineering France. Of course, other aspects also have influences on the company, but for the moment, they don’t immediately imply possible application of new technologies or standards to the company’s projects, whereas the new standard and technologies of communication can directly have impact on Tractebel’s activity.

The aim of chapters VII to IX is to estimate the feasibility of application of the standard IEC 61850 to one electrical substation in Kaléta project, where Tractebel Engineering is responsible for feasibility, technical control and supervision.

In this chapter, we are interested particularly in the understanding of the standard IEC 61850. Some acronyms may be used frequently to facilitate the reading:

- LN for Logical Node,
- LD for Logical Device,
- IED for Intelligent Electronic Device.

VII.1. Generalities

In 1994, the IEC (International Electrotechnical Commission) began to work on a new communication protocol named 61850. This standard is dedicated, originally, to the transmission substations. Today, actors of the hydropower sector are interested too in this standard and considered it as a possible choice for power plants in the future.

There are several advantages covered by this protocol:

- Interoperability: the ability to use different suppliers’ products that are supposedly compatible according to 61850. Thus, this means that clients become more independent because they are not obligated to ask products or services systematically from the same supplier, or to radically change the entire system [51].
• Reduction of wiring in substations: as it comes here to replace the conventional cables by an Ethernet type network, the number of cables, their occupied space and their cost will be reduced.

• Use of information technology: IEC 61850 will allow the energy sector to take advantage of some advanced IT progresses. In addition it is hoped that engineering and maintenance time can be reduced through the use of data that is common to all suppliers.

VII.1.1. Stakes of the standard

During the development of the standard IEC 61850, the major companies such as Alstom, ABB, Siemens, were invited to participate. Thus this standard looks promising for the industrial world and it is essential to take into account its possible consequences and impacts for a company like Tractebel Engineering France. Because it may be that this will be the future standard of communication in the world of hydroelectricity, and even to other areas, for examples, for dispersed generation sources.

Currently, there have already been some substations achieved with the standard IEC 61850. There is no hydroelectric plant yet constructed according to this standard, but the IEC 61850-7-410 part already exists and it defines the communication rules for hydroelectric projects. We expect that other types of plants will be interested in this standard in the future too. Consequently, the IEC 61850-7-420 part defines the communication structure for dispersed generation sources.

VII.1.2. Principles of modeling for the IEC 61850

As defined by the International Electrotechnical Commission, an electrical substation is the "part of an electrical network, consisting primarily of the ends of transmission and distribution lines, electrical equipment, buildings, and possibly, transformers, located at the same place."

An electrical substation often has the ability to transform voltage. Most of the substations have therefore one or more transformers and they may have many other functions, such as switching, breaking and protection capabilities. Generally, for a distribution substation, the high voltage is converted to low voltage. But later in our study case of Kaléta, it will be a power plant switch yard that transforms voltage in the opposite way.
SAS or Substation Automation System is a computer system that enables for example an administrator to communicate with a substation via a computer network. Thus, during the development of such a system, it is necessary to create a general substations model with all the necessary components and features. Then we should specify the exact form of communication. This describes the challenges faced by the IEC 61850 [52].

The following picture shows the conceptual approach of a substation modeling following the IEC 61850. A true physical substation is modeled into a virtual one; the latter contains a detailed data model encapsulating real substation’s objects and functions. The relevant parts of IEC 61850 are also displayed in this picture. Therefore, the substation has a virtual image of itself in a data model suitable for a computer system. This data model is composed of a number of Logical Nodes, which are key objects in this standard’s modeling. A Logical Node can have a number of data objects that are attached to him, and each data object can have a number of attributes. This data model will be explained with more details in the next section.

Figure 5 Conceptual approach of IEC 61850 modeling [53]
VII.1.2.1. Data model

In a substation, it may have one or more physical devices. A physical device contains one or more Logical Devices, a Logical Device may have multiple Logical Nodes. A Logical Node has a number of data objects, who have attributes with values.

The data model is hierarchical; Logical Nodes are the essential elements of this model. Below, we have a diagram of the system data hierarchy of the system data.

![Diagram of the system data hierarchy](image)

A Logical Node represents a particular function in a device (Logical Device) in figure 5 and can be defined as the smallest part of a function that exchanges data [53]. The IEC 61850 Defines 91 classes of Logical Nodes that are grouped into 13 groups according to their functionality, each Logical Node is defined as a class with some attributes.

In a data model, some instances of Logical Nodes can be grouped in a Bay which is defined as a subset of the substation, with common features [54]. This Bay, called "Logical Device", is thus a logical grouping, which does not necessarily correspond to a physical device.
VII.1.2.2. Object-oriented programming

We have mentioned so far some concepts such as classes, instances, objects or attributes. Indeed, these concepts are also used in object-oriented programming methodology. It is a form of programming where data are collected into some structures named data classes.

From a data class, it is possible to instantiate, i.e. to build or generate entities that have the same properties defined by the class they belong to. These entities are called objects. Each data class contains a name, and possibly some variables called attributes and functions called methods.

In [55], the standard defines the common data classes that include attributes and specify the details of the likely use of each attribute.

Figure 7 Example of the class diagram of a substation following the concepts of the IEC 61850
VII.1.2.3. Unified Modeling Language

UML or Unified Modeling Language is a language that is adapted to the object-oriented programming, it allows a graphical representation of different objects, what makes that the system functional divisions as well as the relationships between classes are easy to be viewed and understand.

The following figure is the UML to an electrical substation proposed by the standard.

Figure 8  Object model

It is possible to expand this modeling for a hydroelectric power plant, as the IEC 61850 provides an application wider than electrical substations. We can then add some elements in the class diagram:
Figure 9 Object model for a hydro power plant

VII.1.2.4. The concept of Logical Node

A Logical Node represents a particular function in a "logical device" and can be defined as the smallest part of a function that exchanges data [53]. The standard defines 91 classes of Logical Nodes that are grouped into 13 groups according to their functionality. Each Logical Node is defined as a class with some attributes, and is presented in the form of a table with the necessary information on the operation. The Logical Nodes are the basic elements to model data (cf. figure 10).

Most of the Logical Nodes are defined in part 7-4 of the standard, and in part 7-410 those that are specific to the hydroelectricity field are added.

The name of a Logical Node is always defined by 4 characters. The first character defines the class of the modeled function. The various categories are shown in the following table.
### Tableau 3 Different categories of the Logical Nodes

<table>
<thead>
<tr>
<th>Group Indicator</th>
<th>Logical node groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Automatic Control</td>
</tr>
<tr>
<td>C</td>
<td>Supervisory control</td>
</tr>
<tr>
<td>D</td>
<td>DER</td>
</tr>
<tr>
<td>F</td>
<td>Functional blocks</td>
</tr>
<tr>
<td>G</td>
<td>Generic Function References</td>
</tr>
<tr>
<td>H</td>
<td>Hydro power</td>
</tr>
<tr>
<td>I</td>
<td>Interfacing and Archiving</td>
</tr>
<tr>
<td>K</td>
<td>Mechanical and non-electrical primary equipment</td>
</tr>
<tr>
<td>L</td>
<td>System Logical Nodes</td>
</tr>
<tr>
<td>M</td>
<td>Metering and Measurement</td>
</tr>
<tr>
<td>P</td>
<td>Protection Functions</td>
</tr>
<tr>
<td>Q</td>
<td>Power Quality Events Detection Related</td>
</tr>
<tr>
<td>R</td>
<td>Protection Related Functions</td>
</tr>
<tr>
<td>S</td>
<td>Supervision and Monitoring</td>
</tr>
<tr>
<td>T</td>
<td>Instrument Transformer and Sensors</td>
</tr>
<tr>
<td>W</td>
<td>Wind power</td>
</tr>
<tr>
<td>X</td>
<td>Switchgear</td>
</tr>
<tr>
<td>Y</td>
<td>Power Transformer and Related Functions</td>
</tr>
<tr>
<td>Z</td>
<td>Further (power system) Equipment</td>
</tr>
</tbody>
</table>

The three following characters are often the initials of the performed function, so that it is identifiable. For example, for a circuit breaker, the full name is XCBR, X for switchgear, and CBR for Circuit Breaker.
VI.1.2.5. The concept of Logical Device

A Logical Device is a composition of Logical Nodes. It brings together several Logical Nodes to create a virtual device that represents a more important function. That is a “bigger” piece of equipment than a particular function.

VI.1.2.6. The concept of Intelligent Electronic Device

IED or Intelligent Electronic Device has the following definition in the standard [56]:

«Any device incorporating one or more processors, with the capability to receive or send, data/control from, or to, an external source, for example electronic multi-function meters, digital relays, controllers.

Device capable of executing the behavior of one or more, specified logical nodes in a particular context and delimited by its interfaces.»
In the case of a control system, it is more likely to be a device capable to store and share data, to respond to a command or send a command. Thus, we can consider it like an automaton.

The following diagram shows several examples of different Logical Nodes in an IED. The Logical Nodes involved are PTOC (overcurrent protection), PDIS (distance protection), PTRC (trigger conditions) and XCBR (circuit breaker).

1. Case 1 represents a protection device with two functions, which are wired by classical cable with a circuit breaker.
2. Case 2 shows a protection device with two functions whose triggering device is communicated to the LN of the circuit breaker by a message, via a communication network.
3. Case 3 shows the possibility of having two protection functions in two dedicated IEDs, which can operate both when a fault appears, by triggering via the communications network; messages can be sent independently to the LN of the circuit breaker (XCBR).

Figure 11 Exemples of IEDs composition

Thus, we see that according to the case of configuration, there is the possibility to "digitalize" partially or completely the substation, putting in place a communication network either at the field level only (cf.), either at all levels (see figure 14), i.e. the field level plus
higher level (control room level). In both cases, this is different from the conventional structure where only hardwired copper wires are used everywhere (see figure 12).

Figure 12 Conventional architecture

Figure 13 Conventional architecture at field level only
VII.1.2.7. XML programming language

According to the standard, the modeling system must be designed for different engineering software and is readable by software from different vendors to ensure interoperability which is covered by IEC 61850.

XML or Extensible Markup Language is a programming language that allows storing data characterized through tags. Thus, each user can create their own tags to describe data while keeping the same structure of various elements, the language chosen by the standard is therefore appropriate.

Additionally, XML can be presented in the form of a tree structure, and there is software that allows modifying the XML file without going into the level of code lines, but rather keeping a realistic viewpoint of its contents. Thus, users of the IEC 61850 are not obliged to be trained in XML.

In practice, nowadays, it is possible to make designs of substations according to the 61850 standard while keeping a "graphic" view of things. Actually, design software can
provide the ability to visualize as much as possible the corresponding reality, instead of lines of code. An XML file can be generated automatically once the design is complete.

VII.1.2.8. SCL language

SCL is the acronym for “Substation automation system Configuration description Language”. SCL file is used to describe configurations of communication between IEDs, IEDs’ settings and parameters, communication system configurations, the function structures and the relationship between them.

The SCL language contains multiple file types; each of them is dedicated to a specific purpose:

- The extension .icd (IED Capability Description) describes the ability of an IED, with the optional description of the communication system and the substation.
- The extension .ssd (System Specification Description) gives the complete specification of the substation automation system, excluding the description of the IEDs.
- The extension .scd (Substation Configuration Description) gives the complete specification of the substation automation system, including the description of the IEDs.
- The extension .cid (Configured IED Description) allows communication between an IED and configuration tool [52].

All these files are structured in XML format.

Thus, to stay compliant to the IEC 61850, an IED must have an ICD file, with information about its Logical Nodes or IP address etc. The configuration tool must be able to read the ICD files, to modify the SCD file that gives information about the substation and to add IEDs.
VIII.  Practical application: modeling of a system

In this chapter, we try to model a power plant HV switch yard according to the IEC 61850 standard. However, the interest of this exercise is not only to have a model at the end, because this is also an opportunity to get acquainted with the software and the concepts of IEC 61850. It remains an opportunity to know the level of development of software linked to the standard, the possible advantages and disadvantages of the practical implementation of this standard to a substation such as the one of Kaléta. It’s along an occasion to forecast the development of this field for the future.

VIII.1. Presentation of the system

VIII.1.1.  Presentation of the project of Kaléta

The hydroelectric development project of Kaléta is a prior energy project of Guinean Government; it has a contract value of 446 million USD. Its construction period is provided for 48 months, and its installed capacity is 240 MW. It is hoped that this project will reduce the severe shortage of electricity in Guinea and its neighboring countries as well as providing energy for the development of the mining industry in Guinea [57].

Kaléta project is expected to lead to the following achievements:

- A 70-km access road;
- A roller-compacted concrete dam with a length of 1145 m and a height on foundation of 22 m, the capability of the reservoir is 23 000 000 m³, the height of the nominal drop is 49.2 m;
- A factory incorporated in the body of the dam with three penstocks;
- A hydro plant equipped by three Kaplan type vertical axis turbines with an installed power of $3 \times 80 = 240$ MW with a turbine flow of $3 \times 180 = 540$ m³/s;
- A 220 kV transmission line of about 145 km;
- Three electrical substations.

The work of Kaléta is carried out by the company of China International Water and Electric Corporation. Engineers of the corresponding engineering departments of Tractebel Engineering France take care of the technical control of the project.
VIII.1.2. The HV switch yard of the Kaléta power plant

Kaléta project involves several electrical substations; we choose the HV switch yard where the voltage level is 220 kV (KALETA 220kV) for trials of modeling tools.
Figure 15 Kaleta electrical network
Figure 16 Single line diagram of HV switch yard of Kaleta power plant
VIII.2. Software tools choices

There are several software programs today for the creation and editing of SCL files while remaining compliant to the IEC 61850. Preferably, we will choose software that is designed by third parties, instead of by equipment suppliers such as Alstom, ABB etc. One reason why we make this choice is precisely because the standard is intended to promote independence from suppliers. In addition, it is an opportunity to test the interoperability of IEDs from different suppliers.

The software initially selected for the test is:

- Visual SCL of ASE
- Helinks STS of Helinks
- IEC 61850 SCL Manager of Kalkitech

These three software programs have all existed for several years and offered improved versions or updates, moreover there are already substations automation projects made by using Helinks STS or SCL Manager.

We will make judgments of such software at the end of this section. As a first step, let's look at the overall operation principles of such software.

VIII.2.1. Software principles

As the IEC 61850 standard already specifies requirements on the SCL files editing, the software that we can find are often similar.

In general, software tool includes at least interfaces below to address multi-level modeling of the substation.

- An interface to draw the single line diagram of the substation;
- An interface to manage the Logical Nodes and the IEDs;
- An interface to manage the communication;
- A possible interface to manage more detailed data.
VIII.2.1.1. Single line diagram

To start modeling, the first step is always the single line diagram drawing. The icons of basic components of a substation are already provided by software, this step is relatively easy to do.

Below is the Helinks STS interface for the single line diagram.

![Figure 17 Interface of single line diagram drawing of Helinks STS](image)

In the software of Kalkitech, there are not only components intended for modeling of a substation, but also components for the hydroelectric power plant, or the dispersed generation system. These are actually areas on which the IEC 61850 intends to grow.

However, even during this first step, Visual SCL knows already some fairly serious slowdown problems of the software, especially when the diagram becomes more and more complex. At the end of the diagram, adding a component can even take 10 minutes. Sometimes we can see crashes of the program. One possible explanation of this phenomenon could be that the structure and the interaction of different components can be complex, and it...
involves a lot of data to be treated, even though what we see from the interface is just a diagram.

**VIII.2.1.2. Adding Logical Nodes and IEDs**

Once the single line diagram is established, it is about to add some Logical Nodes and IEDs. Often, another interface is planned for it, while we can keep an idea or a view of the “shadowed” real single line diagram in the background. The advantage of this way of doing is that on the one hand, we can quite easily visualize the link between the Logical Nodes and the corresponding components of the physical world; on the other hand, this corresponds to the designing philosophy of the IEC 61850, which intends to create a “virtual world” through the Logical Nodes, at the level of the communication network.

![Figure 18 Adding IEDs by following single line diagram, with Helinks STS](image)
However, in Visual SCL of ASE, some Logical Nodes are added with the IED of electrical components while it would be more logical to place some of them in IEDs for protection relays.

The addition of the Logical Nodes is quite easy because the IEC 61850 lists and classes already all possible categories of the Logical Nodes.

We often have the possibility to build our own IEDs by entering all the necessary data, or load IEDs that already exist on the market from a database whose access is provided by the software. Loading existed IEDs is obviously more interesting in our case. Major suppliers already have their preconfigured IEDs, and ideally, we can just load them according to our needs, even if a minimum of knowledge of software is required to fit the IEDs to the substation model.

In the demonstration of Helinks, we add LNs in the IEDs, which corresponds to an 'academic' approach, as it allows to understand the concepts of IEC 61850. However, for a more 'industrial' approach, it would be more logical to find, as a first step, the existing protection relays’ IEDs. Then, based on these existing IEDs, we can determine the needs of the LNs.

In absolute terms, it is possible to add IEDs from different suppliers and operate them so that they will work together, it is precisely the interoperability aimed by the standard. However, to our knowledge, in reality, the number of suppliers remains still limited in real projects.

VIII.2.1.3. Communication

Then, we will go to the edition of communication, so that information can be exchanged.

An important concept here is the GOOSE type message (Generic Object Oriented Substation Events). This is a fast message that is transmitted via Ethernet. Thus, in a concrete case of protection equipment, for example, a GOOSE message makes communication between two IEDs possible. We can imagine that when there is a fault in a bay, if the circuit breaker of another Bay should open, the corresponding IEDs to the protective devices will communicate by GOOSE message, and not by the hardwired cables between protective equipment, which corresponds to the classical method.
Thus, there is a need to strictly define horizontal messages between the IEDs and the vertical communication messages. Some IEDs already provide some message types that are likely to be sent, somewhat easing the configuration; otherwise, we must be manually set these messages.

![Diagram of creating GOOSE message without specifying IEDs, with Helinks STS](image)

**Figure 19** Creating GOOSE message without specifying IEDs, with Helinks STS
VIII.2.1.4. Exportation of files

Once we finish all the previous steps for the whole substation, we can export the SCL files. Moreover, a file in XML format can be generated automatically, as well as documentations of modeling in PDF format depending on software, it is at least the case for Helinks STS.

VIII.2.2. Conclusion of the software after tests

In summary, we tested three pieces of software: Visual SCL of ASE, Helinks STS from Helinks, and IEC 61850 SCL Manager of Kalkitech. Contacting with these software providers, we had access to either a trial version, or a number of detailed presentations (this is the case of Helinks) which allows at least grasp its main workings.

Today, Visual SCL doesn't regularly update anymore its database nor offers any improved versions, which means that this piece of software does not match the requirement of
the IEC 61850 and will disappear from the market. On the other hand, Helinks STS and SCL Manager seem to be well positioned, enhanced versions of their software were presented over the past years, as well as a database of the IEDs. In addition, projects have already been achieved through these pieces of software.

All these three pieces of software are pretty friendly in the sense that it is relatively easy to use. However, this still requires a fairly solid knowledge of the IEC 61850 and needs a number of significant manipulations to understand well software, despite the instruction manuals.

Visual SCL knows a very blatant software slowdown when the system becomes complex, in the case of the post of Kaleta, we were witnessing the software crashes frequently. The same phenomenon exists for two other pieces of software, but it was less serious.

The latest version of Helinks STS is quite intelligent in the sense that it is capable of facilitating as much as possible the tasks for users. For example, when we want to add an IED that has been deleted or replaced by another IED, this addition is done quickly because the program can remember and recognize the ancient IED. Another example is the principle of virtual IED: initially, all IEDs are virtual; it is by loading data from IEDs suppliers that the virtual IEDs become real. Thus, it is possible to easily change IED or supplier, without changing the structure of the substation.

However, as we have explained earlier (see VII.2.1.2), this approach is very academic, and does not correspond to industrial use.

Finally, Helinks STS generates a PDF file automatically to explain the functioning and the structure of the automated substation, which allows a quick understanding of it for those who have not participated in the modeling. Once implemented, this option could save time for engineers.

The interoperability of the IEDs is checked by Helinks STS, i.e. the IEDs from different providers communicate without problems. As we had access to an unrestricted version of Helinks STS relatively late, we could not watch this software tool more in detail. A deeper analysis of this tool in the future may be desirable.

There were no more interests to test Visual SCL at this level due to the lack of database.
IX. Reflections on the IEC 61850 with a practical point of view

In this chapter, we will analyze the advantages and disadvantages of the implementation of IEC 61850 from a practical point of view.

IX.1. Issues related to the use of the software tools

We have chosen to test some software tools that are developed by third parties, in order to verify the interoperability of components. In general, this function is well made. Helinks STS and SCL Manager update their database of IEDs from the major suppliers, and while modeling, software is not dedicated to a specific provider. Pieces of software such as Visual SCL of ASE which does stop to update their software will certainly be eliminated over time.

We know that there are already projects using Helinks or Kalkitech, however, Helinks is a good tool for learning the principles of IEC 61850, and seems less effective for industrial use. Kalkitech is capable of modelling normal substations using components from multiple vendors, but according to the selected vendors, the complexity of modeling varies. This means that their software starts to be mature, although it is not yet perfect.

The complexity of modeling can have an impact on the operation of the software tool. The speed of the program is slowing down as the IEDs are added. Nowadays, the record for the number of IEDs used by Helinks STS remains 75 at the moment, it was a project in Australia, half of them were ABB’s IEDs, and another half was provided by Schneider. But generally, we should not exceed 50 IEDs during modeling, if we want to have a tolerable program speed.

Thus, this implies that there is a limit in the complexity of the electrical substation, if we want to adapt it to the IEC 61850. Often, the distribution substations are simpler than power plant HV switch yard. In the case of the HV switch yard of Kaléta project, there are more than 90 current transformers and more than 40 circuit breakers on the diagram. Of course, there are redundancies in the diagram, and depending on the type of IED, it is possible to combine several protective functions in a single IED. But despite this eventual reduction in the number of the IEDs, it still remains very complex, without mentioning the integration of intelligent devices for power and voltage transformers, or switches. Yet, this substation
remains relatively simple as a power plant switch yard, and this could already cause a problem for the design software.

GOOSE messages are very important from the IEC 61850’s point of view. However, it can be difficult to configure with software tools, especially when it comes to make communicate several IEDs from different vendors, since everything would be done "manually".

Actually, to well fulfill the aim of making Kaléta’s HV switch yard suitable to IEC 61850, it’s possible to use some other software tools provided by big equipment suppliers such as ABB or Alstom. However, these tools have a relatively high cost of license for Tractebel who is not specialized only in electrical substations. Moreover, according to IEC 61850, independent third party’s software tools should work as well as others. That’s why we have only taken into account independent software tools.

IX.2. Issues related to the concepts of the standard

An unquestionable advantage of the IEC 61850 is interoperability. This provides autonomy and flexibility regarding various equipment suppliers. In addition, digitization of the substation would allow faster communication, and therefore more able to adapt to the trend of Smart Grids.

However, the standard leaves a lot of freedom to equipment providers, because there are many optional choices provided by the IEC 61850. This complicates implementation of interoperability because equipment can still be very different from one to another according to providers.

From a practical point of view, this substation automation requires new skills for the staff in charge of substations, as well as for the engineers. Indeed, let’s suppose that there is a problem in the functioning of a substation automated according to the IEC 61850 standard, to find out and solve the problem, knowledge of conventional electrical equipment maybe would be insufficient, since an Ethernet structure at least at the control level is in place. But of course there is also the possibility to create systems that facilitate this kind of tasks for staff.

Another topic of discussion can be GOOSE messages. Indeed, the GOOSE messages will be very used in substations if we adopt the IEC 61850. It is to send a message every 4ms via Ethernet, for a number of times, without verifying that the message reaches the destination. Even though in principle GOOSE is promising, we cannot be fully confident at the moment. Because the substations have a very important role in the electrical networks, a
small risk can lead to a very serious consequence. Thus, it happened sometimes to put cables parallel to Ethernet, in order to ensure the proper functioning of the communication. This contradicts somewhat the starting ideas of GOOSE, which aims to simplify communication.

In the case of the power plant HV switch yard of Kaléta, it has a very important role because the hydroelectric power plant is a key project on the energy map of Guinea. A possible implementation of IEC 61850-compliant substation is risky for several reasons:

1. The IEC 61850 has not yet been tested in practice for a project as important as Kaléta with an independent software tool;
2. It is difficult (or expensive) to train engineers or technicians who are able to work under the environment of the IEC 61850 because concepts are not easy to understand immediately, and competences in computer science and communication are required also. Knowing that, education in Guinea remains undeveloped; Guinea is one of the countries with the highest rate of illiteracy in the world, i.e. more than 60% in 2011. This results in a greater lack of competent staff.
3. With the computer tool today, if we choose it independently regarding electrical equipment suppliers, the HV switch yard of Kaléta may remain relatively complex to model.

In reality, these problems mentioned above can be generalized in some way, even if they remain particularly true in Guinea. Because we are facing a dilemma: IEC 61850 seems to be well suited to the electrical grid of the future, because it would make substations powerful enough for all functions expected from “Smart Grids”. However, the operation principles of an automated substation are much more complex than a classical substation; this means training of concerned technicians and engineers, but also a possible functioning risk.

Furthermore, software today is not yet suitable for all types of substations, depending especially on their complexity level. They would be therefore still much less suitable for hydro power plants that have many more components than a substation, even if the standard goes already in advance and defines necessary things for this domain.

For these different reasons, we can conclude that technically, designing Kaléta HV switch yard by following IEC 61850 is possible in absolute term, but if we choose independent computer tools (which is quite suitable in the case of Tractebel Engineering France), the feasibility will still be low. And from a practical view, with the country’s situation, this is also risky.
X. Conclusion

In this article, we have tried to identify the aspects and technologies of smart grids that can be interesting for Tractebel Engineering France, so that engineers of the company could give advices about smart grid to the clients. Another aim was to estimate the feasibility of application of the standard IEC 61850 to one electrical substation in Kaléta project, where Tractebel Engineering is responsible for feasibility, technical control and supervision.

These two aims may seem independent, but in reality they are linked, as among all concepts and technologies that are in relation with smart grids, electrical substations automation play an essential role. And this automation would be achieved according to the standard IEC 61850. It is also the area that would be interesting for Tractebel Engineering France and the pole HEM (Hydro-electrical-mechanical), since projects may include studies of substations. Moreover, IEC 61850 is already beginning to expand in the area of hydropower, which is one of the main activities of the company.

The important thing is to know the difference between theory and reality, whether it's smart grids in general or the IEC 61850. Very often, the articles on these topics talk about technologies and standards without mentioning the financial consequences, the security, the difficulty of the establishment, etc. Furthermore, any product wants to appear as 'intelligent' today, while it does not necessarily correspond to real criteria for intelligent networks.

Regards directly to Tractebel Engineering France, IEC 61850 seems to be the standard of the future. In fact, there are already substations made according to this standard which would be probably promising. In other words, all equipment tends to become more communicating and digitalized. However, time is a critical factor. On the one hand, if the computer tools have made progress in recent years, they are not yet hundred percent mature. On the other hand, the construction of substations according to the IEC 61850 is recent, we probably don’t know all the problems that may exist.

For all these reasons mentioned above, adaptation of Kaléta’s HV switch yard to IEC 61850 seems to be premature for Tractebel Engineering France, even though it’s already doable technically. However, we can expect a better feasibility of this kind of projects in the future, as computer tools and technicians or engineers become ready to IEC 61850.
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