Introduction

In the last years, Smart Grids have attracted the attention of academic researchers and R&D corporations, becoming one of the most promising technological developments and, at the same time, one of the most fascinating challenges. But, what is the revolution contained in the Smart Grids concept? In the following, an answer to this question is This is done providing a sketch of the historical evolution of the electric energy supply starting from traditional electric networks and accounting for the main technological innovations occurred during the last and the present century.

Traditional electric networks

The electric energy has intrinsically two main characteristics: i) it can be easily transported at very long distances but ii) it can hardly be stored. As a consequence, in traditional systems, the electric energy must be produced when it is needed. This fact has led researchers and engineers to think of the electricity as a “service” energy that, on one hand, results from the transformation of another form of energy (chemical, mechanical, solar among others) and, on the other hand, requires a final transformation in another form to be effectively used. So, according to this concept, the traditional electric system has been thought as a very complex and wide infrastructure allowing energy to be produced at very long distances from the place in which it is needed.

Unfortunately, as any other physical system, the electric infrastructure consisting of Overhead Transmission Lines (OHL) and buried cables presents some losses (basically due to the Joule effect on OHL/cables resistance) that have to be minimized in order to increase the overall system energy efficiency. Considering the fact that the Joule losses are proportional to the square of the current flowing in the infrastructure while the power to be transmitted depends on the product between the voltage and the current itself, it is apparent that the smaller the current, the higher the energy efficiency of the whole infrastructure. This consideration should lead to the conclusion that the electric system should be operated at the highest possible voltage value. On the other hand, security issues imply a voltage level upper bound depending on the specific network portion (an overhead transmission line can be safely operated at very high voltage levels because the probability of a contact with people is quite modest; on the other hand, the distribution system that provides voltage to houses is characterized by a highly lower voltage level because the safety issue is of primary importance).

According to this reasoning, it is apparent that the optimal topology of an electricity network is a very wide infrastructure characterized by different portions with different voltage levels connected together.

That is the reason why the classical electric network is divided into four main subsystems: i) the generation subsystem (typical voltage level laying in the range 10-20 kV), ii) the High Voltage (HV) transmission subsystem (voltage level 400/230 kV or 132 kV for sub-transmission subsystems) , iii) the Medium Voltage (MV) distribution subsystem (voltage level between 15 and 20 kV) and iv) and the Low Voltage (LV) utilization subsystem (400/230 V). Of course, to ensure the electric continuity of the whole system, it is necessary to have at disposal devices that should receive in input one voltage level and produce in output another voltage level: the transformers.

As transformers working principle is based on the electromagnetic induction law, an electric infrastructure with the above described characteristics cannot be operated in DC. That is probably the main historical reason why the traditional electric network is an AC system. A sketch of the typical traditional electric network can be found in Fig. 1.

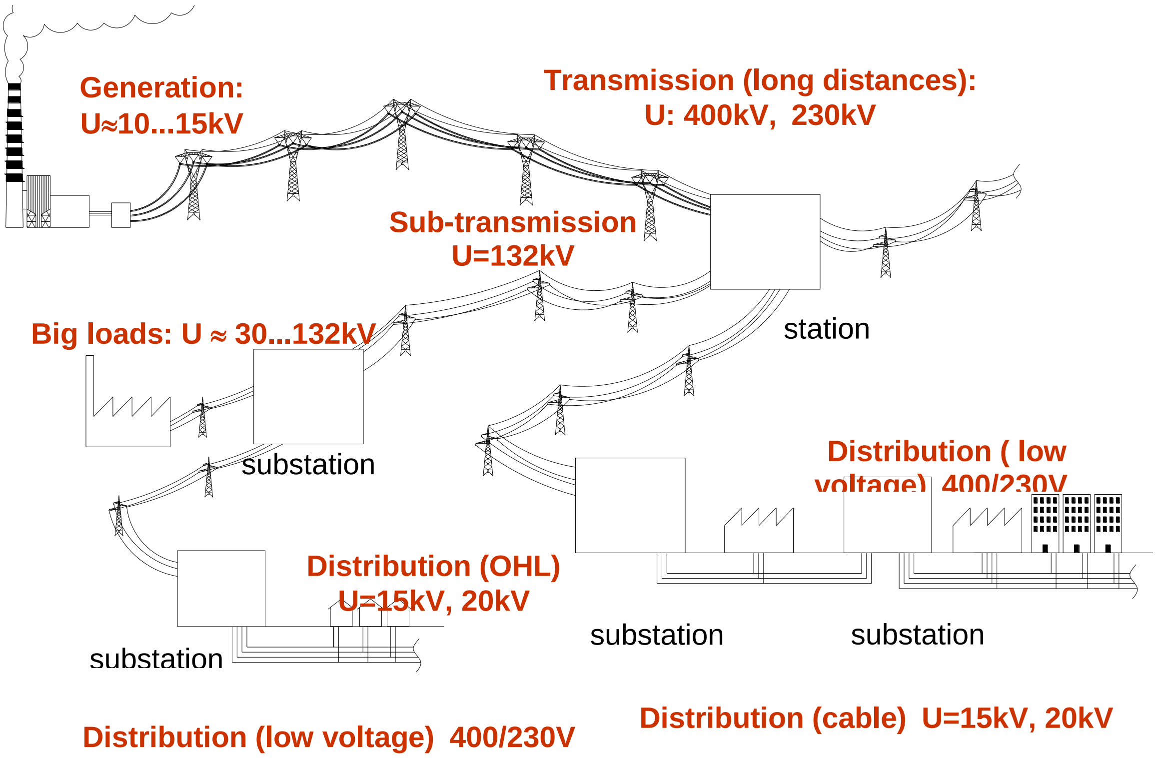

Fig. 1: Traditional network structure

As can be seen examining Fig. 2, the transmission and distribution networks are different from a topological point of view; the structure of the first is typically meshed in order to ensure that any point of the network is fed in at least two alternative ways. On the other hand, the distribution network is normally radial with noteworthy advantages in the protection system design (see [1] for details).

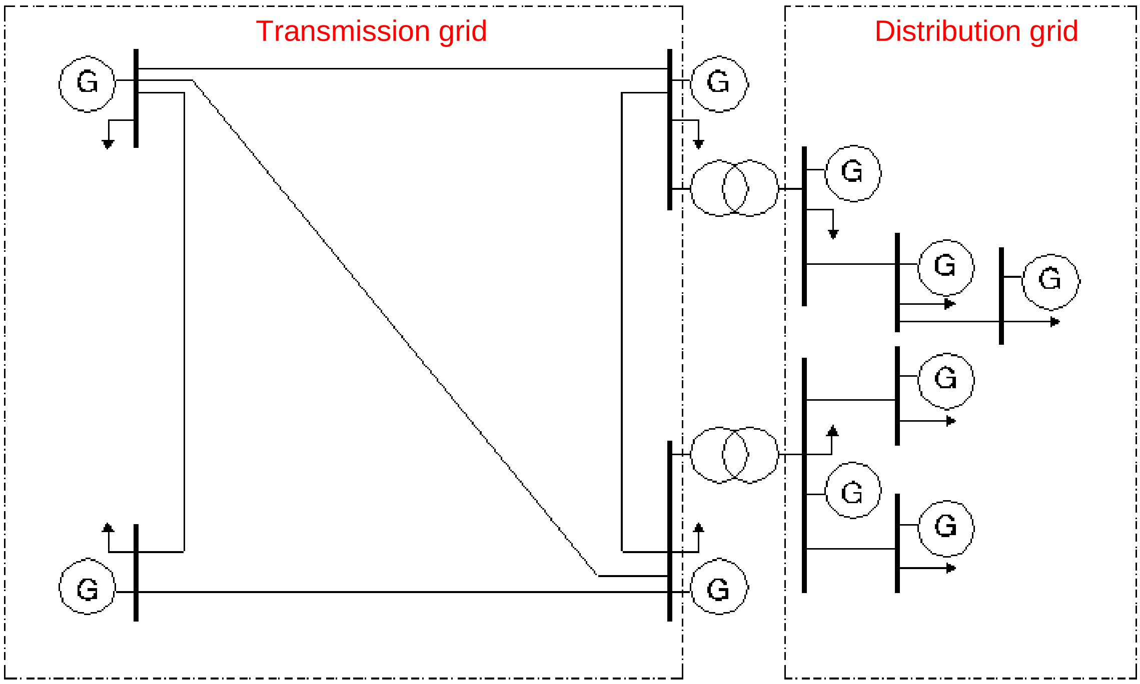

Fig. 2: Transmission and distribution networks topology

Moreover, the great majority of the traditional electric system is operated as a three phase balanced system essentially for two main reasons: i) from an economical point of view, this guarantees the possibility of transmitting the same amount of power as in a one phase system with a significant copper saving (see for [1] details) ii) the instantaneous power is constant which becomes extremely important when dealing with induction machines.

Finally, in traditional networks, the possibility of regulating the quantities of interest at the desired values is limited to a few cases, namely:

1. the active power produced by synchronous generators, acting on the machine governors
2. the voltage (or the reactive power) at the terminals of synchronous generators by means of an Automatic Voltage Regulator (AVR) acting on their field voltage

3. the voltage at specific points of the network, with the aid of On Load Tap Changer (OLTC) Transformers or fixed capacitor banks

In such a structure, it is apparent that there is no way to control the active/reactive power flows in the transmission and distribution networks which are determined essentially by the solution of the load flow equations.

Summarizing, the main characteristics of a traditional electric network are:

1. a very wide and interconnected infrastructure
2. the energy sources are basically a reduced number of plants producing a significant amount of power
3. AC operating conditions in order to ensure the interconnection of different voltage level subsystems by means of transformers
4. three phase balanced system mainly for economical/power quality reasons
5. a limited possibility of controls, mainly concentrated on synchronous generators, thus leading to a reduced degree of flexibility in the infrastructure

The first "revolution": power electronics

In 1948, Bardeen, Brattain and Schockley from the Bell telephone laboratories invented the transistor, causing a revolution in electronics. In 1956, in the same laboratories, the first thyristor was produced, then commercialized in 1958 by General Electric (GE). From then, many different devices and converters have been invented, with a significant acceleration between the end of the 80s and the first 90s [2-3].

Power electronics has, since then, changed the power system concepts and operation, introducing the possibility of converting an AC source into a DC one and vice versa. This has had a significant impact both on transmission and distribution systems. In the first case, the introduction of the so-called Flexible AC Transmission Systems (FACTS) [4] has allowed the control of power flows in the transmission infrastructure and has opened the possibility of transmitting power in DC, with a meaningful reduction of voltage drops due to the absence of reactances (see Fig. 3 where the Unified Power Flow Controller (UPFC) scheme is depicted, consisting of a series compensator, the SSSC and a shunt one, the STATCOM)

Distribution systems have increased their flexibility thanks to the so-called Custom Power Devices that have allowed solving a lot of power quality problems [5], like voltage sags, power factor correction, harmonic active and passive filtering among others (see Fig. 4).

The introduction of power electronic devices has determined a significant change in the concepts of power systems, especially because it has relaxed the constraint of operating the network as a three-phase AC system (items 3 and 4 of the initial checklist) and because it has increased its flexibility and power quality thanks to the introduction of new control actions (item 5).

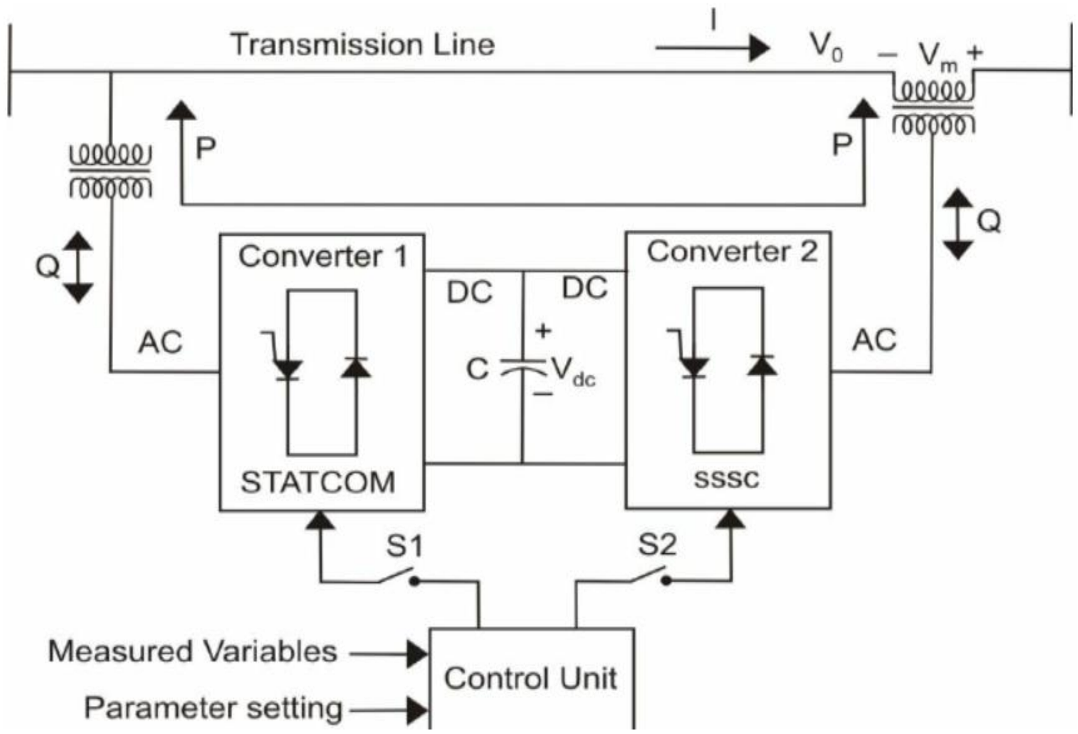

Fig. 3: UPFC scheme as an example of FACTS devices (adapted from [6])

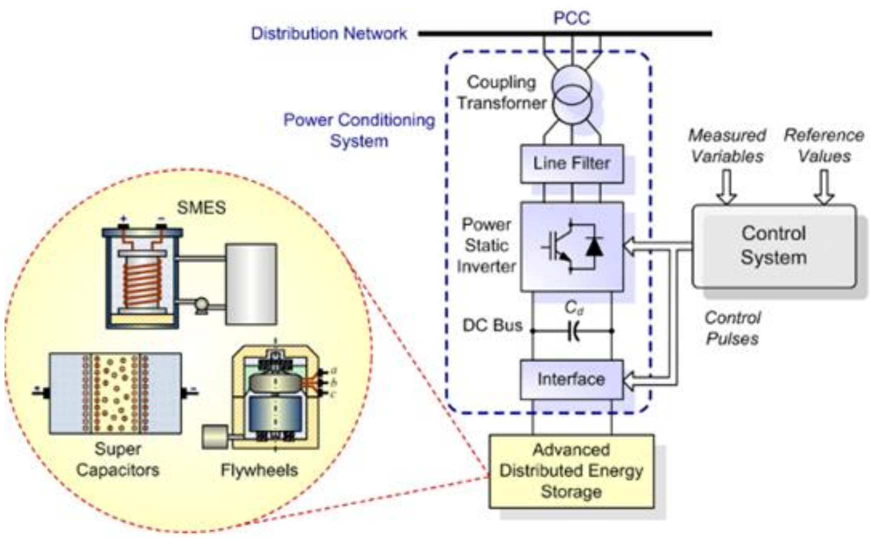

Fig. 4: Custom power device example

The second revolution: the Distributed Energy Resources (DER)

Distributed power technologies are not new. Before the development of large-scale power plants in the early twentieth century, all energy requirements—including heating, cooling, lighting, mechanical and electric power—were supplied at or near the point of use [7]. The movement to central station power plants started in 1891, when George Westinghouse assembled the first AC system in Telluride, Colorado. Since then, thanks to the lower power production costs, central production units became more and more widely employed. The era of central station power was underway, and distributed power technologies were consigned to providing back-up and remote power. But technology change is constant. Today, technology advances have enabled the development of a new breed of distributed power technologies that have the ability to rival the cost and performance of central station power plants, but in a much smaller package. In [7], Owen among three phases in the global power system: the Legacy Distributed Power Era (1890–1910), the Central Power Era (1910–2000) and the Integrated Energy Systems Era (2000–present). The first one was characterized by small and local power plants that provided energy to their local area through DC grids. Then, the central power era was determined by the economy of scale that produced the increase of larger power plants, some of them exceeding 1 GW. Finally, the present era is characterized by ”the rise of distributed power transforming power networks around the globe into integrated energy systems [7]”.

So, in the present era, also item 2 of the initial checklist may not be respected.

But, what about item 1? In other words, is it possible to revolutionize the concept of electrical infrastructure by relaxing the constraint of a single infrastructure extended in space and interconnected? To answer this question, it is necessary to go deep into some properties of DERs.

Distributed Energy Resources can be basically divided into two broad categories: Renewable Energy Sources (RES) and Conventional Energy Sources (CES). If, on one hand, the first category is more appealing as its primary energy source is free of charge and does not negatively impact on the environment, on the other hand its intrinsic stochastic nature makes it impossible to dispatch a RES as a traditional power plant. Consequently, keeping in mind the concept according to which “the electric energy must be produced when it is needed”, it seems impossible to make the infrastructure disappear.

Moreover, the wider and wider diffusion of RES in the modern electric grid has opened the very important issue of integrating them into the network. As a matter of fact, the majority of control logics, protection schemes and management systems that are consolidated in traditional networks fail whenever facing systems with a significant penetration of renewables. Below some examples:

- the classic dispatching based on the equality of incremental costs [1] is not valid anymore, as one has to account for a certain amount of unpredictable power production
- the usual protection schemes adopted for distribution networks relies on the concept that the power flow is unidirectional (i.e. from the transmission network to the loads). This idea can cause improper tripping when dealing with systems in which loads can be also fed by local generators
- the standard power/frequency regulation based on the droop technique [1] that ensures a proper subdivision of the load increase/decrease among the machines assumes that all the generators participating to the regulation can rely on a power reserve that can be used in any moment, which is not the case when dealing with a PV or a wind unit

Consequently, the possibility of changing item 1 of the initial checklist claims for a new revolution which does not consist of the invention/production of new devices, but of a higher level of integration. And it is to give a different answer to this question that the concept of Smart Grids was born.

The third revolution: Smart(Micro)Grids

The concept of Smart Grid (and of Microgrid) aims at moving from a centralized, monodirectional grid (Fig. 5) to a bidirectional grid characterized by distributed energy (Fig. 6).

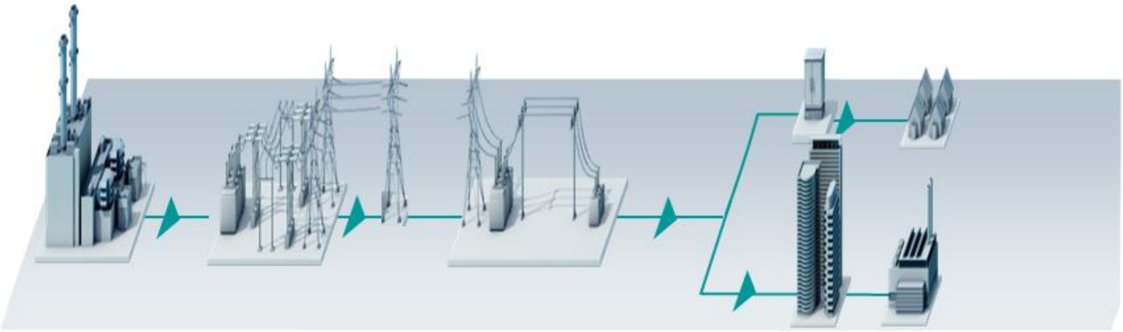

Fig. 5: Unidirectional, centralized grid (Source: Siemens)

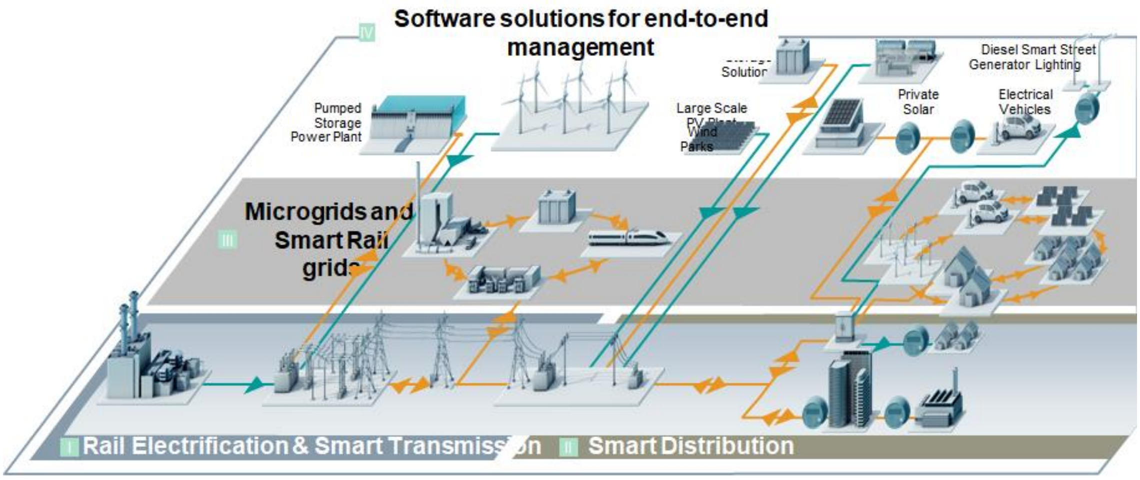

Fig. 6: Micro Grid (Source: Siemens)

A Smart Grid is an electrical grid which includes a variety of operational and energy measures including smart meters, smart appliances, renewable energy resources, and energy efficient resources [8]-[9]. Electronic power conditioning and control of the production and distribution of electricity are important aspects of the Smart Grid[8].

The first official definition of Smart Grid was provided by the Energy Independence and Security Act of 2007 (EISA-2007), which was approved by the US Congress in January 2007, and signed to law by President George W. Bush in December 2007. Title XIII of this bill provides a description, with ten characteristics, that can be considered a definition for Smart Grid, as follows:

"It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system to maintain a reliable and secure electricity infrastructure that can meet future demand growth and to achieve each of the following, which together characterize a Smart Grid: (1) Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid. (2) Dynamic optimization of grid operations and resources, with full cyber-security. (3) Deployment and integration of distributed resources and generation, including renewable resources. (4) Development and incorporation of demand response, demand-side resources, and energy-efficiency resources. (5) Deployment of 'smart' technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation. (6) Integration of 'smart' appliances and consumer devices. (7) Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal storage air conditioning. (8) Provision to consumers of timely information and control options. (9) Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid. (10) Identification and lowering of unreasonable or unnecessary barriers to adoption of Smart Grid technologies, practices, and services."

In the concept of Smart Grid, particular attention is being given by academic and industrial researchers to the so-called Microgrids.

According to [10], the definition of Microgrid is “a cluster of loads and microsources operating as a single controllable system that provides both power and heat to its local area”. If one analyzes the definition, it readily follows that a Smart Grid is characterized by i) devices and ii) infrastructures. The devices present in a Smart Grid can be classified in three main categories (see Fig. 7):

a) DERs (that can be in turn divided into RES and CES),
b) Distributed Storage systems (DS) and
c) Electric and thermal loads.

From the infrastructure point of view, one typically has:

a) an electric infrastructure
b) a thermal infrastructure
c) an ICT infrastructure

The electric and thermal infrastructure are coupled whenever Combined Heat & Power (CHP) devices are present in the Smart Grid; moreover, the ICT infrastructure allows a central "brain" to optimally manage all the devices present in the Smart Grid.

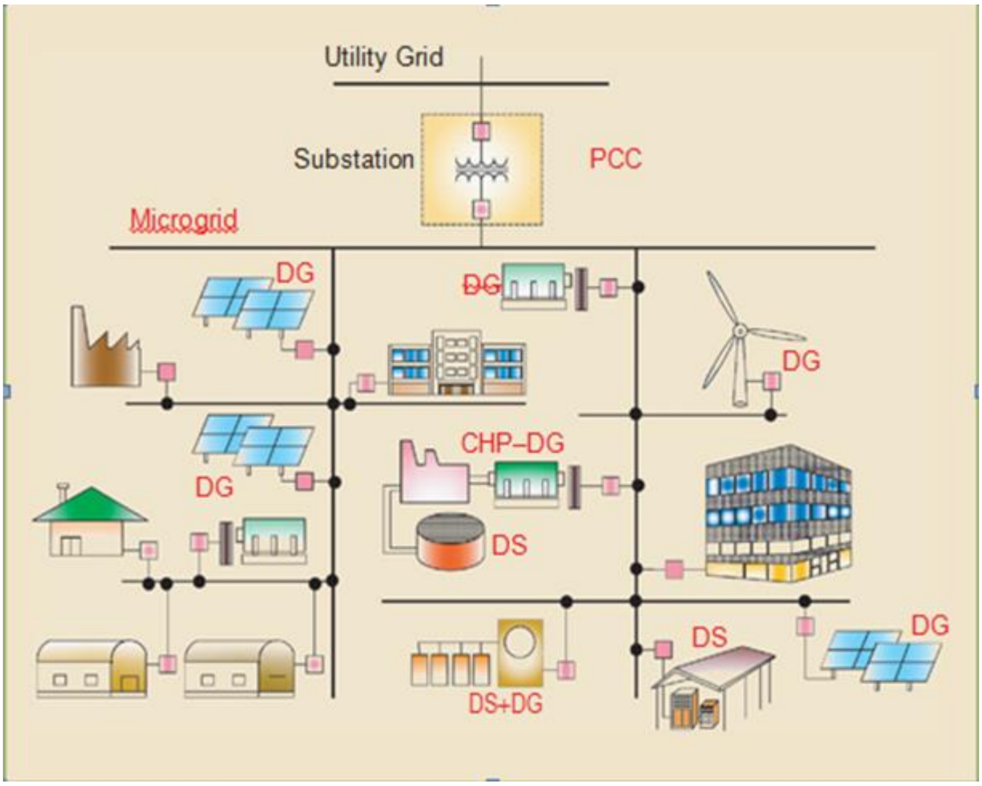

Fig. 7: Smart Grid structure (from [8])

As specified in the end of the previous subsection, it is the integration of all these devices and infrastructures that allows the possibility of changing the paradigm of the electricity (and thermal energy) supply. In particular, as will be outlined later on in the book, the Energy Management System (EMS), making use of the ICT network, dictates the production of CES, the charging/discharging of DS and the eventual participation of specified loads (in case of demand/ response strategies) starting from the electric and thermal request and the RES production. This can optimize the energy behaviour of the Smart Grid and, in principle, can lead to a situation in which it can be independent from the public network.

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