SUPERGRIDS AND THE NEW CHALLENGES TO FACE

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ABSTRACT
In recent years electrical energy systems have undergone radical changes. The earliest innovations in MV and LV distribution systems brought about the development of smart grids, i.e. intelligent networks that, among countless other benefits, allow to exploit the renewable energy dispersed on the territory which would not otherwise be recovered. More recently, there have been momentous changes also in the HV and EHV electrical transmission systems that had already turned into Mega Smart Grids, i.e. large, high-voltage networks where some typical functions of smart grids had been implemented. In the future, in order to take advantage of the large energy amounts from renewable sources, such as wind in the North Sea and PV in the Sahara Desert, the different European mega smart grids may turn into one huge network called Supergrid, which will not only have important intelligent features but also a large number of submarine HVDC connections. The paper highlights the new opportunities offered by Supergrids, as well as some of the problems to be faced, such as voltage stability in huge systems whose mere size would have been unthinkable just a dozen years ago.

KEY WORDS
Supergrids and mega smart grids, Power system voltage stability, Renewable energy sources, Energy geopolitics.

1. Introduction

The concept of a "super grid" began to take shape in the 1960s with reference to the emerging unification of the Great Britain grid. The name Supergrid instead appeared in 1990 to describe the part of the interconnected British grid with a rated voltage greater than 200 kV. In 2001 the same term was used at a conference in Brussels co-organized by the European Wind Energy Association and Atricity to describe the possibility to capture wind energy from the North Sea (about 150 GW by 2030) through a wide submarine grid connected to large hydro reserves in Scandinavia, in order to serve central Europe with such a stabilized power level as nuclear or traditional thermoelectric power plants can assure. More recently, this concept was enlarged by involving two main higher frameworks, the former an EHV structure superimposed upon the traditional regional transmission systems, the latter the advanced intelligent abilities necessary to solve a number of problems, among which transmission congestion, quick diagnosis, protection coordination, management of wide area sensor networks, fast control actions, etc. [1-8].

The term Supergrid is presently used with reference to a continental or transcontinental-wide mega grid conceived to link both local generation and distant renewable energy sources with the populated areas through the use of intelligent, integrated, highly coordinated features. This wide area transmission network takes advantage of control, automation, information and communication technologies so as to better manage the generated, stored or transmitted energy, either in normal or emergency conditions, promoting at the same time a large, effective, liberalized and transnational energy market.

Throughout the world now three main Supergrids are being developed: the SuperSmart Grid (Europe), the Unified Smart Grid (U.S.) and the Asian Super Grid.

2. Energy independence

An important, urgent issue in present energy geopolitics is the European dependence from the Russian Federation in the importation of natural gas that is extensively used by some U.E. countries also for electricity production. In the U.S. a strongly interconnected grid among states was proposed to reach a complete energy independence, which will engender the further advantage of a remarkable reduction in greenhouse gases, responsible of pollution and global warming. In the U.E. a substantial energy independence may be achieved by exploiting energy from the North Sea (wind) and North African Regions (PV), but also from Ukraine and Kazakhstan (gas and oil reserves), implementing redundant links with both submarine cables and overhead lines. In this scenario, the realization of an electrical main ring across European boundaries will be of paramount importance. In possible emergency situations, and accepting higher electric energy production costs, the target of zero net imports can be achieved. As a matter of
In fact, in a contingency situation, also due to possible terrorist attacks, load shedding actions and start-up of existing, obsolete fossil power stations might be usefully activated; moreover, during the first critical hours also fast diesel generators, dispersed on the territory, could be started up and hydro storage used.

As already mentioned, often in addition to the normal high-voltage overhead lines, in a Supergrid submarine cable lines are also used for High Voltage Direct Current (HVDC). In this case, an important, attractive technology, which is also highly effective in conjunction with a Supergrid, is the use of superconducting cables suitable for the simultaneous transmission of electrical energy and liquid hydrogen; the latter, maintained to a very low temperatures, may also fulfill the further, important task of operating the cable in conditions of superconductivity. Especially in the case of low energy demand the required hydrogen may be produced also by the high temperatures already existing nuclear plants.

In conclusion, different technologies can be integrated in a Supergrid to achieve energy independence, allowing to deploy renewable energy from very distant geographical zones (sometimes also different time zones), and therefore to substantially smoothen the PV, wind and ocean generation intermittency due to the very different weather and sunshine conditions from zone to zone at any given moment.

As regards energy independence from the point of view of the energy market [9], it is believed that a Supergrid should be designed keeping in mind the presence of renewable as high as possible, so that energy trade would be limited only by the amount of electricity that contractors can bring to market.

### 3. The voltage collapse phenomenon in mega-smart grids

As explained in previous sections, a Supergrid is a large synchronous network able to transmit large energy amounts also from renewable sources. In some implementations the direct-current network consisting of HVDC lines is a completely separated layer from the alternating-current transmission system. In this case, a Supergrid may be also defined as a Mega Grid since it is not very different from a wide-area synchronous transmission system. A number of smart grid features are sometimes incorporated in these high-voltage systems [10-12], such as Wide Area Sensor Networks (WAMS), which transform the obtained power network into a Mega Smart Grid.

Because of the competitiveness required by the development of a global energy-liberalized market, the very high-voltage lines of a Mega Smart Grid are designed so as to minimize operating costs and investments. This usually involves a significant utilization of EHV electric lines, which are required to carry very high power, up to 2-3 times the natural loading, especially in emergency conditions. From the point of view of the network management, this situation can engender depressed voltages in large network areas, especially when synchronous generators are called to provide reactive power close to their overexcitation limit [13]. The problem is often complicated by the fact that the distributed generation from renewable sources does not normally cooperate in controlling the network voltage profiles [14-17], because reactive power is either not frequently provided by DG or, in the best of cases, only a modest quantity is supplied, often also with a fixed power factor [18]. These conditions can clearly lead to very critical situations that may also lead to the outage of very large networks.

The basic concepts of the voltage collapse phenomenon are already known in the literature [19], and can be introduced with reference to the simple circuit in Fig. 1 where $Z_L[\beta]$ indicates the load impedance and $Z_U[\beta]$ the longitudinal equivalent impedance of a transmission line.

![Fig. 1. A simple equivalent circuit to explain the voltage collapse phenomenon.](image)

The line is fed from node $S\cdot S'$ (sending end) with $E_S$ voltage, which is for simplicity assumed as constant (node with regulated voltage). The $Z_L$ load impedance is supposed as variable in its modulus and argument. The voltage $E_R$ at the receiving end (R-R'), the active power $P_a$ required by the load and the current $I$ as a function of $Z_L$ and $Z_U$ can be obtained by means of the following equations:

$$E_S = (Z_L + Z_U)I; \quad E_R = Z_U I. \quad (1)$$

With simple trigonometric transformations, the following relations can be obtained:

$$I = \frac{E_S}{\sqrt{(Z_L \cos \beta + Z_U \cos \phi)^2 + (Z_L \sin \beta + Z_U \sin \phi)^2}} = \frac{E_S}{Z_L \sqrt{1 + \left(\frac{Z_U}{Z_L}\right)^2 + 2 \frac{Z_U}{Z_L} \cos(\beta - \phi)}} \quad (2)$$
Usually it is $Z_U > Z_L$. If the $Z_U$ load impedance is progressively reduced, keeping $E_S$ and $\varphi$ constant, the voltage $E_R$ will progressively decrease as the current increases. The power $P_u$ is obviously nil for both $Z_U = \infty$ (open line) and $Z_U = 0$ (short-circuited line). Differentiating and equaling relation (4) to zero, the maximum value of $P_u$ can be easily calculated:

$$P_{u,max} = \frac{3E_S^2 Z_U \cos \varphi}{2Z_L (1 + \cos(\beta - \varphi))}$$

(5)

Ultimately, the power absorbed by the load when $Z_U$ decreases, with $E_S$ and $\varphi$ constant, increases up to the maximum value ($P_{u,max}$) for $Z_U = Z_L$, then it decreases. The corresponding voltage value, defined as critical voltage, can be calculated using the following formula:

$$E_{R,crit} = \frac{E_S}{\sqrt{2(1 + \cos(\beta - \varphi))}}$$

(6)

Or, taking relation (5) into account, the critical voltage can also be computed by means of the following simple relationship:

$$E_{R,crit} = \sqrt{\frac{P_{u,max} Z_L}{3 \cos \varphi}}$$

(7)

The main results of the above considerations are visually represented in Fig. 2, which is reported as an example.

A better representation for an equivalent load would take into account the behavior of asynchronous motors, which play a very important role in the voltage collapse phenomenon due to their slowdown and consequent impedance reduction during a busbar voltage dip [20]. After fault clearing, voltage may be so low that the motors continue to slow down and voltage collapses. A suggested equivalent dynamic circuit for the load based on the above concepts is shown in Fig. 3.

Fig. 4 shows the flow chart of a proposed algorithm for the voltage analysis during a transient caused by a fault in order to verify if the network maintains voltage stability or otherwise collapses.

As concerns mega smart grids and the voltage collapse phenomenon, the possible coordination and control systems must make a massive use of measurement technology based on Phasor Measurement Units (PMU). First of all, this technology must quickly identify important and unwanted energy fluctuations caused by high-power renewable sources; afterwards, these undesired power flows should be redirected and redistributed in order to maintain the necessary stability of the transmission system, possibly anticipating and avoiding, as far as possible, also any voltage instability conditions [21].

In this context, the adoption of predictive methods can also be very useful [22], as well as a thorough evaluation of other specific technical aspects of high-power renewable generation, [23-24].
4. Conclusion

A Supergrid is the new frontier of very high-voltage power systems, integrating the intelligent features of a large electric energy transmission area with local smart grids into one global network. The proposed European Supergrid aims to capture huge amounts of renewable energy from many wide areas, namely the North Sea (wind), the Scandinavian peninsula (hydro), Iceland (geothermal) and North Africa (solar). These renewable, carbon-free energies, different in form and often coming from geographical zones very distant from one another, will also allow to overcome another great problem of renewable sources, namely generation intermittency, since at any given moment there will be surely areas producing energy. Within this extraordinarily interesting scenario, it is however necessary to solve a number of problems inherent to the new Supergrids, among them the issue of assuring the voltage stability of a very complex system. In the paper, some considerations about the voltage collapse phenomenon are presented and discussed with reference to a large EHV transmission system.

References


