# SUPERCONDUCTING MAGNETIC ENERGY STORAGE
## *A Technological Contribute to Smart Grid Concept Implementation*

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Abstract: The urgent need to solve existing problems in the electric grid led to the emergence of the new Smart Grid (SG) concept. A smart grid is usually described as an electricity network that can intelligently integrate the actions of all players connected to it in order to efficiently deliver sustainable, economic and secure electricity supplies. Smart grids should be flexible, accessible, reliable and economic, bringing great new challenges into grid management. In order to implement this concept it is necessary to consider the operation of several new devices in the electrical grid. A class of these potential devices is Superconducting Magnetic Energy Storage (SMES) that present, among other features, very fast response times. SMES devices can play a key role in helping to overcome several grids' faults. In this paper it is described the possibility to integrate SMES into SG, and the advantages of this integration.

# 1 INTRODUCTION

Nowadays electric power producers must obey several laws that, among other things, force them to produce from a distinct mix of sources, reduce their carbon emissions and assure an adequate response to power demand. These aspects reveal the necessity to modernize the electric grid. Currently, only one third of the potential energy contained in the several existing thermal sources is successfully transformed into electricity and about 8% of this total electricity is lost, only in the transmission lines (Farhangi 2010). An obvious conclusion is drawn: the existing electric grids are inefficient.

Besides this, the increasing number of human population results in an increasing electricity demand. In 2020, it is estimated that the consumption of electricity will surpass 27,000 TWh. When compared to the consumption of the year 2000 (15,400 TWh) this means a 75% increase (Garrity 2008). This increasing demand accentuates existing issues in an electric grid. These are commonly accepted to include, amongst others (Benysek, 2007):

- Voltage dips and swells.
- Frequency oscillations and harmonic issues.
- Phase unbalancing.
- Hierarchical grid (failure of one element can lead to a major failure of the grid).

Today it is believed that the answer to these issues is based upon a fundamental concept: Smart Grids (SG).

The future electric grid must then be provided with intelligence, having several fundamental features: ability to remotely monitor and control the grid elements and self-healing capability to automatically overcome faults (F. Li et al. 2010). This creates a tremendous challenge, because in order to assure these characteristics several devices/protocols are needed, as well as a huge standardization effort (Gungor et al. 2011), amongst other complex aspects. Many of these devices/protocols already exist and just need to be applied to SG. One such technology with potential application are superconducting devices, as superconducting magnetic energy storage (SMES) and superconducting fault current limiters (SFCL) (Hassenzahl et al. 2004; Hassenzahl 2001; Malozemoff et al. 2002). The integration of these two devices into SG is desirable because these devices can address several of the existing issues in electric grids. Throughout this document it will be

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discussed the advantages in integrating SMES systems in a SG, and also, although briefly, the advantages of SFCL.

## 2 SMART GRIDS – SHORT OVERVIEW

### 2.1 Current Research Projects

The need to transform the existing electric grid in a SG has originated a large number of research efforts, in order to assure the quality of the future electric grids.

European Union created in 2005 the SmartGrids European Technology Platform with representatives from industry, production and transmission companies, researchers and regulators, to generate objectives and tasks with the main purpose of obtaining a common vision about electric grid in Europe, after the year 2020 (Comission, E., 2005; Comission, E., n.d.).

In USA several initiatives arise in parallel, in order to study the electric grids of the future, and how to perform the transition for those grids. Among these initiatives, highlight the following: IntelliGrid (EPRI, n.d.), which already achieved important results (Hutson et al. 2008; McGranaghan et al. 2008); Grid Wise (Cherian & Ambrosio 2004), created by the Department of Energy; Modern Grid Initiative (Pullins 2007), from the National Energy Technology Laboratory; and Distribution Vision 2010 (Fanning & Huber 2005), a consortium of 6 companies aiming to develop mechanisms and devices to apply in SG.

All these initiatives have the common goal of develop intelligent electric grids. However one of their greatest challenges is how to implement the transition from the existing electric grid to a SG, as the former cannot be simply disconnected. Furthermore, during several years, it will be necessary to assure the coexistence of the two types of grids in harmony. It is still necessary to answer to this challenge, and current research lines have already focused their attention on these issues.

### 2.2 Smart Grids Main Features

Considering the common goals of the several research groups presented in the previous section, the Smart Grid must address the features presented in figure 1.

The characteristics outlined in figure 1 are essential to the success of SG. Existing electric grids are mainly unidirectional. To allow a full control over the grid, both information and energy must flow in a bidirectional way.

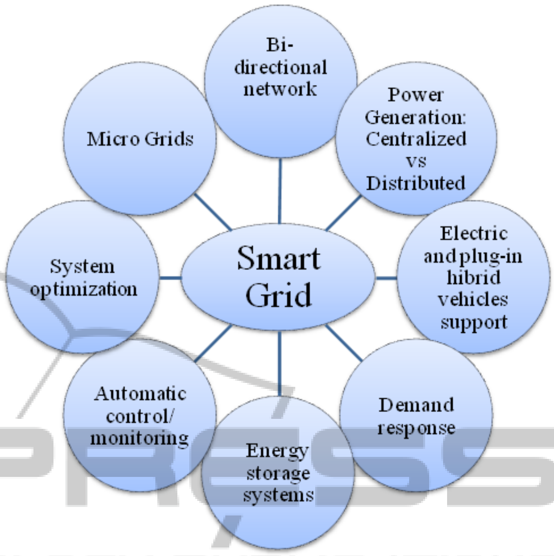


Figure 1: Main characteristics of a Smart Grid.

With the increasing production of electric energy from renewable sources like sun and wind, electric grids face a new challenge: the intermittence of these resources. Along the next years, the penetration of these resources in the electric grid will increase, which creates several additional issues that need to be solved. Those issues can be of various types, and be present in distinct grid segments (Ipakchi & Albuyeh 2009):

- Transmission grid: superconducting wind generators up to 10 MW are currently foreseen for offshore applications (Abrahamsen et al. 2010). Wind farms with such an amount of intermittent power raise stability restrictions.
- Distribution grid: together with huge wind farms projects (high power capacity) there is an increasing number of distributed generators (DG) as small wind farms and photovoltaic plants, with low power production. The intermittence of solar and wind resources, along with the increasing penetration of these small power plants brings out the need to carefully control all the existing elements in a grid (including spinning reserve elements), and to minimize local impacts (voltage sags and frequency oscillations) that can spread to other adjacent grids. The electric grid can accommodate medium and low voltage distributed energy resources, called Microgrids (MG) (Hatziargyriou et al. 2007). Each MG cannot only have the capacity to locally produce electricity, but also to store it and

exchange it with the grid.

- Interconnection: it is widely accepted that interconnection standards have to be unified.
- Operational Issues: the instability of the solar and wind generation raises operational issues, as it is necessary to assure the correct grid operation when these resources are not producing the expected amount of electric power. For instance, the abrupt lost of power from these sources can lead to grid instability, with consequences as voltage sags or frequency oscillations.
- Electric/plug-in hybrid vehicles: the expected increasing penetration of those types of vehicles brings additional problems. Additional grid capacity may be needed for charging purposes, and the impact of charging stations in the grid must be taken into account.

All the previous challenges must be solved, assuring that SG behaves as expected, always optimizing grid operation (maximum operational efficiency and maximum control of power) and ensuring its sustainability without harming the environment.

One possible approach for some of the above issues consists on the integration in the grid of Energy Storage Systems (ESS). ESS can accommodate different technologies, in order to increase its reliability. For example, ESS can combine batteries, ultra-capacitors and SMES, to assure a quick and efficient response to a contingency situation.

Finally, SG must include the central concept of Demand Response (DR) (Rahimi & Ipakchi 2010). DR transfers to the users the responsibility to adapt their consumption profile to the production of the grid in which they are inserted. It promotes the stability of the electric grid by minimizing demand in peak periods. With the liberalization of electricity markets in several countries and with the DG using mainly solar panels, small electricity consumers are now becoming simultaneously producers (prosumers). This new concept generates a new challenge, as grid operators cannot know when these prosumers are injecting energy in the electric grid and by that decreasing global energy needs. It is necessary to review the load profile and provide tools to simulate and monitor the behavior of the prosumers, in order to assure maximum grid stability (Grijalva & Tariq 2011; Lampropoulos et al. 2010).

## 2.3 Smart Grids Control and Monitoring

Real time monitoring and control of the SG elements is essential to assure reliable grid operation. This implies that every element must present data processing capacity (Massoud Amin & Wollenberg 2005). Implementation of autonomous processing allows the electric grid to have bidirectional data and energy flow. However, it brings up several new issues because it is essential to assure the security of the data flow, as well as the creating regulatory entities that must have the capacity to control both energy and data flows.

The control of a SG also brings some new challenges regarding the type of controllers to be developed, considering centralized or decentralized control units, and the robust integration of these controllers, allowing them to coordinately overpass several contingencies that might occur(Arnold 2011).

It is also necessary to clarify the tasks to be performed by human operators. These can be divided into three main areas:

- Monitoring (the data in the grid).
- Analyzing (events, grid access, etc).
- Controlling (stability, fault occurrences, etc).

The research in these three areas generated the concept of Smart Control Centers (Zhang et al. 2010). These centers have a huge processing capacity to solve the already mentioned issues that can occur in an electric grid.

One other concept that arises with SG is smart metering, implemented by the so-called Advanced Metering Infrastructure (AMI) (Vojdani 2008). AMI's introduce new functionalities that can help both producers and consumers. These functionalities include, among others, real-time monitoring of consumptions and tariffs by the consumers, and pricing differentiation by producers. Since most of these functionalities are software based, virtually an unlimited number of different options can be implemented. Another important functionality is the possibility of small producers to choose when to sell the electricity, thus obtaining better prices. The implementation and integration of these AMI's is a great step to evolve to a fully liberalized electricity market.

## 2.4 Simulation Tools and Devices

To perform a correct analysis of SG, and to develop new concepts, it is essential to use simulation tools. The existing electric grid simulation tools lack required functionalities to simulate SG environment (Arritt & Dugan 2011). This means that another challenge is to adapt these existent tools, or design new ones, in a way that they can perform proper SG modeling, real-time simulation and fault simulation.

These tools also have to be scalable, robust and user-friendly.

Although it is essential to have simulation tools for SG power flow, a SG can only exist with proper creation/integration of devices allowing coordinated and reliable behavior. Among those devices, highlights power electronics based ones, where three types of concepts are crucial: Flexible AC Transmission Systems (FACTS), High Voltage Direct Current (HVDC) and Smart Transformers (Jiang et al. 2006; Hanson et al. 2002; P. Kadurek et al. 2010; Petr Kadurek et al. 2011). These three technologies are envisaged to help providing faster dynamic voltage control and accurate power (active and reactive) stability control, over the SG. There is a great variety of systems relevant to FACTS and HVDC, like Synchronous Static Compensators (STATCOM), Static Series Synchronous Compensators (SSSC) or Unified Power Flow Controllers (UPFP). These power electronics based devices can be combined with other concepts, potentially maximizing grid stability effects. These can include, as already mentioned, superconducting devices like SMES. The integration of superconducting technologies in SG has many potential advantages, which are presented in the next section.

# 3 SMES – OVERVIEW

Superconducting Magnetic Energy Storage (SMES) systems store energy in the magnetic field of a superconducting coil. Considering the inductance and current flowing in the coil, namely $L$ and $I$, then the stored energy, $E$, is given by

$$E = \frac{1}{2} L I^2 \tag{1}$$

Initially, SMES systems were built with low temperature superconductors (LTS, with typical operating temperature at 4.2 K), either because high temperature superconductors (HTS, with operating temperature typically above 40 K) had not yet been discovered, but mainly because LTS wire manufacturing process was already mature. The costs of these LTS SMES were however not viable, not only due to the SC wire but also due to the price of the cryogenic system (estimated as 15% of the total cost of the all system) (Hsu & W.-J. Lee 1993). The discovery of HTS and the development of ceramic materials based wires, allowed that costs associated with cryogenics substantially decreased. The problem was that the price of HTS wire was initially one order of magnitude higher than LTS wire, making HTS SMES systems still economically unfeasible (Tsukamoto 2005). Nowadays, as the price of HTS wire is decreasing (especially Y-Ba-Cu-O coated conductors), there is a all new future for HTS SMES (Lehner, 2011).

The general scheme of a SMES system is shown in figure 2.

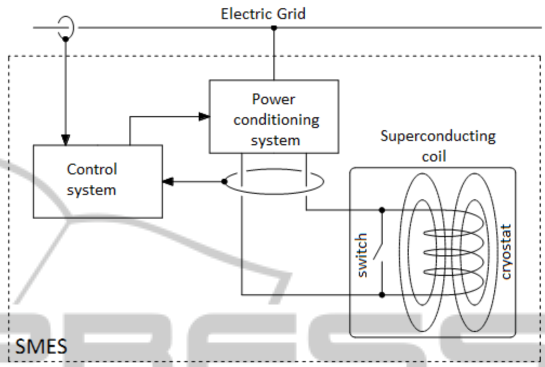


Figure 2: SMES diagram.

A SMES system is composed by the following main elements (X D Xue et al. 2006):

- Superconducting coil (SC), with a switch that changes between charging and discharging mode. The coil must be inside a cryostat that maintains the required temperature, and there is also a mechanical structure associated with the coil, in order to withstand the Lorentz forces developed. The switch is implemented by a power electronics converter.
- Power conditioning system (PCS), a bidirectional power electronics interface which converts electric power from DC to AC, when charging/discharging the SC coil. The PCS main component is a Voltage Source Inverter (VSI) or a Voltage Source Converter (VSC). There are several topologies that can be used (X D Xue et al. 2006).
- Control system (CS), which manages the exchange of energy between the SMES system and the grid and also allows grid synchronization. The most common control strategy is based on pulse width modulation (PWM) techniques, but other approaches are possible (Molina & Mercado 2011).

From our point of view, and comparing to other existing energy storage systems (ESS), SMES presents two major advantages:

- Fast response time (1-5 ms, only limited to the commutation speed of the PCS components and the bandwidth of sensors).
- High efficiency: including cryogenic losses the efficiency of SMES system is theoretically higher than 90%. Other ESS's have efficiencies around only 70% (Buckles & Hassenzahl 2000).

These two advantages are only possible because energy conversion in SMES is purely electrical, whilst other ESS involve either electrical-chemical or electrical-mechanical energy conversion.

Figure 3 contain a comparison of discharge time and power ratings for several existing ESS.

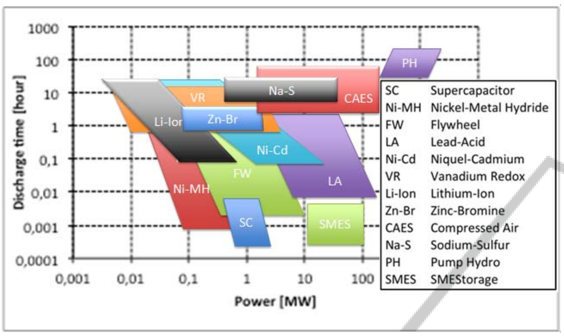


Figure 3: Comparison between ESS's power and discharge time.

As seen in figure 3, SMES systems have a very high power density, but discharge that energy in a very short time, making it a device with low energy density. Table 1 contains a comparison between SMES and batteries, considering power and energy density (Tixador, 2008).

Table 1: Comparison between SMES and batteries. Adapted from (Tixador, 2008).

| | Specific Energy (Wh/kg) | | Specific Power (kW/kg) | |
|---|---|---|---|---|
| | Actual | Theoretical | Actual | Theoretical |
| **SMES** | ~ 1 – 2 | ~ 1 – 10 | ~ 10 – $10^4$ | ~ 10 – $10^5$ |
| **Batteries** | ~ 10 – 200 | | ~ $10^{-3}$ – 10 | |

Considering the specific power and specific energy of SMES, makes them known as power devices rather than energy devices. This limits the applications of SMES systems. In order to build a 5.25 GWh SMES is would be necessary to have a 1000 m diameter and 19 m height LTS SC coil (Tixador, 2008). This is technically and economically unfeasible (Hassenzahl et al. 2004). On the other hand, smaller SMES systems are perfectly feasible. An 800 kJ (0.22 kWh) SMES for military pulsed power source, with a coil with 0.8 m diameter and 0.18 height, is presented in reference (Tixador et al. 2005); while a 1 MJ (0.28 kWh) SMES with a diameter of 0.57 m and a height of 0.65m is described in reference (Liye et al. 2008). Considering these examples, it is expected that in the next years only small SMES systems will be feasible, that is, with rated energy up to a few MJ. These devices are usually called µSMES, and they can solve several existing issues in the electric grid, as explained later in the paper.

# 4 SUPERCONDUCTING APPLICATIONS IN SG

As already mentioned, superconducting based devices that can potentially contribute to efficient operation of a SG are SFCL and SMES. SFCL is briefly explained in the sequel, and SMES applications are subsequently detailed.

## 4.1 SFCL

Superconducting fault current limiters limit the current under a grid fault (mainly short-circuit) without tripping switchgears or interrupting it, thus minimizing the effects in the grid. Once the fault is cleared the SFCL becomes naturally invisible to the grid, without requiring any human intervention. SFCL may take advantage of the non-linear impedance of HTS material, but other approaches are possible (Mathias Noe & Steurer 2007). The feasibility and advantages of SCFL have already been demonstrated (Paul et al. 1997; Khan et al. 2011; Kovalsky et al. 2005; Juengst 2002). There are two main topologies (Pina et al. 2010), according to the insertion method of HTS material in the line, either in series (resistive topology) or magnetically (inductive).

## 4.2 SMES

Considering the main SMES characteristics presented in section 3, these devices find several potential applications in electric grids. Nevertheless, since the time SMES were conceptually presented (Ferrier, 1970) several unfeasible applications have been proposed. The values presented in Table 1 consider only the superconducting coil and the supporting structure. Yet, as previously described, SMES include other major devices, as power electronic converters; magnetic radiation shielding for people and equipment protection; and cryogenic system. Considering e.g. the project described in (Kreutz, et al., 2003), where a 150 kJ SMES for an uninterruptible power application is described, the weight of the coil is about 200 kg, while the weight of the whole system is more than 8 tons. This corresponds to an energy density of 0.21 Wh/kg for the coil, which drops to $5.1\times10^{-3}$ Wh/kg for the SMES, and a power density of 0.1 kW/kg for the coil, droping to $2.5\times10^{-3}$ kW/kg for the whole system. In this project, the major contribution to the mass of the system corresponds to the iron magnetic shield, with almos 7 tons. It is worth to mention that this can be minimized by using toroidal coils rather than solenoidal (thus nearly eliminating all stray flux), or by means of active shielding or special arrangements of solenoids, although increasing complexity of the system or storing less energy as in the case of toroidal topology (Tixador, 2008). Considering the energy stored in this SMES, it is easilly concluded that it is about a tenth of a typical 12 V, 40 Ah car battery. Thus, in spite of all possible improvements, SMES physics excludes these devices from applications which include bulk energy storage, namely supplying load peaks, storing night generation for diurnal use, or eliminating long voltage sags (lasting several seconds or more), which are often proposed in the literature.

Under these considerations, the main envisaged applications for SMES are:

- Grid stability: a SMES unit can absorb low frequency oscillations and stabilize the grid frequency as a result of transients. Since a SMES control both active and reactive power it is a good solution to stabilize MG with a high level of penetration of renewable energy sources (Rabbani et al. 1999; Mitani & Tsuji 1993; Mohd. Hasan Ali, Toshiaki Murata, et al. 2007).
- Power quality improvement: some industrial consumers have sensitive loads with strict requirements on power quality. A SMES unit can smooth or eliminate grid disturbances (e.g. voltage dips during few cycles), which is made possible by the fact that SMES have very fast response times (sometimes less than a cycle) as seen before (Torre & Eckroad 2001).
- Uninterruptible power supply: under a grid shutdown, SMES are able to maintain stable energy supply during startup of emergency groups or other slower ESS (Xue et al. 2005).
- Reactive power flow control and power factor correction: depending on the power converter, SMES provides independent control of active and reactive power (P. D. Baumann 1992).
- Wind farms applications: with the constant increasing of the DG, the resource whose penetration degree in the electricity production system has increased more substantially is wind. In electric grids of the future, wind farms will play a very important roll. Being an intermittent resource, it is essential to assure stability and operation of the grid in which wind is used as a renewable resource to produce electricity. Besides, due to fast and abrupt changes in wind speed, the output power and voltage of generators and consequently of a wind farm can vary considerably. The application of a SMES system is an envisaged solution to minimize these fluctuations, assuring that grid stability is not affected by it (Ngamroo et al. 2009; Asao et al. 2007; W. Li et al. 2009; Nomura et al. 2005). On the other hand, when grid is facing disturbances, SMES installed in a wind farm can minimize transients so that the wind turbines are not affected. This plays a major role in wind turbines transient stability during grid disturbances (Kinjo et al. 2006; M.H. Ali, Minwon, et al. 2007).

In spite of the economic costs still associated with HTS materials and cryogenics (which are expected to decrease with the advent of superconducting technologies), SMES systems are multi target devices that find several potential applications in an electric grid, where they can compete with other ESS.

## 5 CONCLUSIONS

The constant need to assure a best power quality in the electricity market is forcing electricity producers to evolve from existing grids into SG paradigm. In order to assure an efficient and reliable SG operation, it is necessary to adapt, implement or develop energy storage technologies (amongst others). SMES is one concept that can play a major role in SG. There are various advantages in using these energy storage systems when compared to other existing solutions, as the ability to provide high power (up to hundreds of kW) in short time (from milliseconds to seconds). This ability provides the opportunity to quickly react to grid issues, minimizing the effect of these issues. Also, by independently controlling active and reactive power it is possible to easily correct power factor. By exploring unique characteristics of SMES and Superconducting materials, it is possible to maintain stability levels in an electric grid in a more easy way that it was by only using conventional devices. Nevertheless, SMES dissemination still lacks demonstration projects where research and development results can be verified by utilities and other participants in the energy sector.

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