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Superconducting Magnetic Energy Storage Systems (SMES) for Distributed Supply Networks

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Executive Summary

The need to develop energy supply systems, to increase their efficiency and to be able to store energy in large quantities for future technological and social challenges has provided that research and regulations in the electricity sector are oriented in this direction. In this context, electricity distribution networks are oriented towards distributed networks, where small relocated generation sources are created, or in very disparate locations, with small supply sub-networks. All of this is controlled and monitored by means of an electronic supply monitoring and control system.

The sources of generation for which they are mainly betting on this type of networks are mostly renewable, photovoltaic and wind energy sources. To this must be added an energy storage system that can guarantee supply at all times.

Currently, the main energy storage system available is pumping water. Pumped energy storage is one of the most mature storage technologies and is deployed on a large scale throughout Europe. It currently accounts for more than 90% of the storage capacity installed at a European level. The main problem that it provides is the large size and the physical characteristics that are required for its installation. Another problem is what we could consider as the "self-discharge" of this storage system, the evaporation of the dammed water.

Other systems include chemical systems, such as hydrogen storage (as an energy vector, where many resources are being put into its development and implementation); electrochemical, such as lithium batteries; thermal, such as latent heat storage; mechanical, such as Fly Energy Storage (FES) or Compressed Air Energy Storage (CAES); or electrical, such as supercapacitors or Superconducting Magnetic Energy Storage (SMES) systems.

SMES electrical storage systems are based on the generation of a magnetic field with a coil created by superconducting material in a cryogenization tank, where the superconducting material is at a temperature below its critical temperature, Tc. These materials are classified into two types: HTS—High Temperature Superconductor, and LTS—Low Temperature Superconductor.

The main features of this storage system provide a high power storage capacity that can be useful for uninterruptible power supply systems (UPS—Uninterruptible Power Supply).

In addition, they are also useful for the regulation and control of voltages, suppression of network fluctuations, which helps the integration of renewable energies in the energy system.

The problem of implementing a storage system is due to two main factors, regulatory and economic. Regarding the first, an excess of regulations or a lack of it can limit its implementation or help its implementation and its diffusion. In this sense, depending on the structure of each country, we can find different legislative levels. Thus, for example, in the case of Spain, different regulatory levels must be taken into account, with the aim of guaranteeing an adequate inclusion of SMES systems, promoting their use and regulation in manufacturing systems. These levels can be summarized in:

1. European Union (EU), through the corresponding Community Regulations or Directives.
2. National, through ordinary laws, Royal Decree-Law or Regulations (Royal Decree, Ministerial Order, Circulars, Resolutions…).
3. Other regulations of regional application, such as Decrees or Orders.

In relation to the regional regulatory level (Autonomous Communities), it is very limited, except for the possibility of both economic and administrative aids for its implementation.

In other countries, such as the United States, energy policy is set by the Department of Energy (DOE—Department of Energy), through an energy plan approved for the medium/long term (Energy Policy Act of 2005) or Japan with its Basic Energy Plan (*Enerugi Kihon Keikaku*).

The second problem that this storage system must face is economic. To know the viability of an investment of this type and the possible economic benefits of using this type of system, several aspects must be taken into account:

- Investment costs: the construction costs of the system, which will depend on the size and technology to be used, the electrical costs of the system or the costs of the auxiliary systems.
- Operation and maintenance costs: Depending on the size of the plant and a factor related to the lifetime of it.
- Financial costs: To be taken into account in medium and large size installations.

Among the benefits, it is necessary to take into account the times of network unavailability, considering that during this time there are companies or factories that are not producing and are generating considerable losses, as well as the possible environmental benefits due to the non-emission of greenhouse gases. Greenhouse gases (GHG) or other gases that are harmful to humans.

But in order to analyse the penetration of this type of energy storage systems in the energy system, it is necessary to analyse where it is in relation to the electrical network. In this sense, everything points to the distributed generation of electricity, where there are small generators interconnected and monitored to the network.

On the other hand, it must be taken into account that the world population tends to be urban, for example, more than 80% currently live in a city in Spain compared to 65% who did 50 years ago. This phenomenon is widespread in all countries of the world, which implies that energy management, generation and distribution models should be oriented towards the development of intelligent cities or Smart Cities, which seek to increase the efficiency of different levers of action, such as power generation, construction, mobility or administration and social services, as well as the improvement of the operation of the network or the incorporation of renewable energies.

In relation to the levers of the Smart Cities, some crosscutting elements to all of them allow to obtain the necessary synergy to increase the management efficiency that was mentioned. There can be found among these elements:

- Information and communication technologies.
- Systems sensorization.
- Security/cybersecurity.
- Construction and manufacturing materials.

It is important to analyse the characteristics of energy storage systems, such as the SMES system in Smart Cities, in relation to the generation and support of electrical energy, given its characteristics. These systems, during charging and discharging, can help to withstand large power peaks, such as starting motors or in other industrial processes that require very low response times and high capacity for punctual power supply.

Even with everything, despite the characteristics that a storage system of this type can provide, it has some shortcomings that currently cannot be supplied with the technology developed for SMES systems, such as the low energy density that they have. To complement the support systems for the generation of electrical energy, there is the possibility of carrying out a hybridization of the storage systems. The idea is to look for a system with high power density and low response times, such as the SMES system, with systems that can store large amounts of energy, like batteries, CAES system or through water reserves with reversible pumps.

Among the possibilities of hybridization of the storage systems, we can talk about systems in Active Parallel, in Passive Parallel or in Cascade, depending on the needs that are required at each moment and situation.

Knowing the limitations of the distribution networks, generation and storage systems are important to know the possibilities of implantation and inclusion of new systems to the electrical network. In relation to this, SMES storage systems allow to provide support to new electricity supply networks.

On the other hand, there is the need to find energy storage solutions for the processes and elements that can interact with the network. One of the important points is the charging and autonomy system of electric vehicles. Not only the possibility of intelligent systems where one of the generation/storage systems of the network is through the SMES system, but the internal storage element of the vehicles implies a storage system with high power density.

The growth in sales and manufacturing of electric vehicles, as well as the regulations aimed at suspending sales of internal combustion vehicles (Diesel or Gasoline) in the coming years, makes essential to find solutions that allow the autonomy of vehicles or the recharging time of these improve and can resemble the current internal combustion vehicles.

Despite the fact that lithium-ion batteries have a high power density, necessary to start the electric traction motor of this type of vehicle, another storage element is required capable of providing the necessary power at specific moments.

The new electric vehicles have a range of a few hundred kilometres with a fully charged battery and in perfect condition (there is a phenomenon of capacity degradation, so the capacity of the batteries is not always the initial one) and a battery recharge time of around hours or minutes, despite the fact that there are systems that can recharge very quickly but that can affect the life of the batteries.

It must be borne in mind that the advantages that including an SMES storage system can provide can be set against the disadvantages that it entails. These disadvantages provided by this system are mainly two; the first is the need for a refrigeration system for the coil so that it is at a temperature below the critical temperature of the coil material at all times.

As for the second, it is the size of these devices and the weight, given the specific and energy density of these devices. Another of the possibilities of these elements is in processes, whether connected to the grid or on an island, where renewable generation sources are combined with mixed energy storage elements, with elements of high energy density with others such as the SMES system.

In these systems, the need to control at all times the quality of the electricity provided, from renewable sources, from the network or from storage systems and for proper functioning of the process machinery is essential to allow the system to extend its useful life.

Contents

Chapter 1
Introduction

Currently, among the main challenges that are presented for the coming years is the reduction of the emission of Greenhouse Gases, GHG, among which are the energy generation systems, in order to fight climate change. That is why being able to develop technologies that guarantee electricity supply and can improve the quality of supply is essential.

Related to this we may find energy storage systems, such as the superconducting magnetic energy storage system, SMES. This system has been researched and developed in order to improve its operating characteristics, such as the investigation of new materials to increase the critical temperature of the coil [1], or by researching new manufacturing processes [2]. Knowing how the device is, the main characteristics of these are Table 1.1.

The device is made up of the superconducting coil, a cryogenization tank to keep the coil below the critical temperature and the auxiliary systems that allow the operation and cryogenization of that coil, through a control and sensor system, as described shows in Fig. 1.1.

In order to see the possibilities of development in electrical systems, a study oriented towards the analysis of the possibility of evolution and implementation of the superconducting magnetic energy storage system (SMES) must be defined and planned. To do this, we have sought to analyse the different areas where any device must act and focus in order to have an impact and be able to be implemented.

In the first case, it seeks to analyse the regulatory and economic aspects that may affect a storage system of this type so that it can develop and "compete" in the electrical system, specifically for the Spanish electrical system. In this sense, an adequate regulatory base, that is to say from the Public sector, can allow storage to gain momentum in the energy mix and that different technologies, such as SMES or CAE, for example, can provide their advantages to production and power supply.

In addition to the above, the economic aspect is essential. On the one hand, the cost of the device must be analysed, both in terms of investment and in terms of maintenance, based on its useful life. As seen above, this technology is not fully

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Table 1.1 Main characteristics of a SMES [3–8]

Daily self-discharge (%)	Energy density (Wh/L)	Specific energy (Wh/kg)	Power density (W/L)	Specific power (W/kg)	Power (MW)	Response time	Discharge time	Suitable storage duration	Efficiency (%)	Lifetime (year)	Lifetime (cycles)
10–15	0.2–8	0.5–5	1000–4000	500–2000	0.01–10	< 5 ms	ms-min	min-h	> 95	20 +	100.000

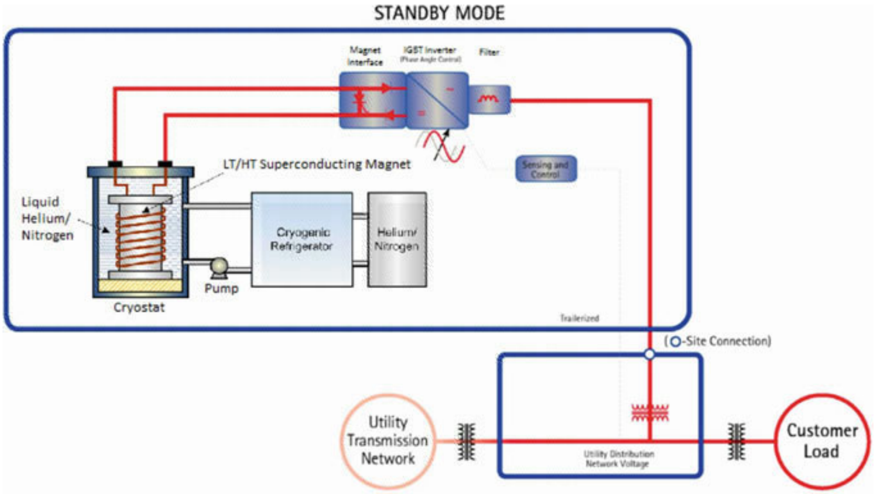

Fig. 1.1 Basic scheme of the system SMES [3]

developed and the manufacturing and maintenance costs are relatively high. On the other hand, the economic benefit that the use of these storage systems can provide in an electrical system where it will be implemented must be taken into account.

The total cost of a system of this type is given by the investment, operation and maintenance costs and by the financial costs, according to [3].

It must be taken into account that the construction and maintenance processes have been improved and can be reduced, in fact the operation and maintenance costs are around 2–3%, according to [9].

In relation to the possible benefits that its implementation would entail, the articles developed show the possible economic and environmental benefits [3]. In the Spanish electricity system, as a reference, it must be borne in mind that in recent years investments have been made to improve the infrastructure and the network control and monitoring system, as well as the electric power generation systems.

With this, the need for an anti-interruption power system, UPS, such as the SMES storage system, can be shown. As shown in Fig. 1.2, it can be seen that availability in recent years has improved slightly thanks to the improvements made, but a lot needs to be done to avoid possible supply problems [10].

On the other hand, the amount of Energy Not Supplied (ENS) and the Average Interruption Time (AIT) do not improve in relation to availability, as shown in Figs. 1.3 and 1.4. This is due to the increase in installed power, of the order of 9.21% despite the closure of some coal plants [10].

On the other hand, the environmental benefits are more than remarkable, as shown in Table 1.2, which shows the decreases in the main harmful substances, such as CO_2, CO, SO_2, NH_3 or NO_x in recent years, produced solely by the power generation from coal. These can also be considered an economic benefit, since millions of euros are invested every year for conditions caused by pollution [11, 12]. According