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Superconductivity in the Electric Power System

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Abstract. Superconductivity is a state of certain materials in which they lose resistivity (they become perfect conductors) and expel any magnetic field from within (they become perfect diamagnetic).

Both properties make superconductors an ideal candidate for use in electrical applications, despite the drawback that the superconducting state only appears when its temperature drops below a certain critical temperature. which, in the best case, is not higher than 77K (−196°C).

Nevertheless, many specific superconductivity applications have been put into service (as particle colliders or MRI scanners) and many others are under development in different maturity levels (TRL). In this group there are some of the more interesting electrical applications as cables, energy storage, or fault current limiters.

This article presents a brief explanation of the principles of superconductivity for a better understanding of its applications in general, and electrical applications in particular. Then, a review of the state of the art of the most interesting superconducting devices for the electrical power system is presented, as well as some possible future consequences of the use of this technology.

Key words. Superconductor, superconductivity applications, electrical applications of superconductivity.

1. Introduction

Superconductors are materials that exhibit zero electrical resistance and the expulsion of magnetic fields when cooled below a certain, so called, *critical temperature*, T_c (between 4,2 and 77K, depending on the material) [1]. The absence of Joule loss allows the transport of current densities 3 orders of magnitude higher than conventional conductors such as copper or aluminium. These properties were discovered at the beginning of the 20th century and their applications have been a challenge for Electrical Engineering ever since, despite the drawback of working at such a low temperature.

In fact, superconductivity can improve (or already has) the technology in a wide range of electrical applications [2], including power generation, electricity transport and distribution, energy storage, electrical protection, and high magnetic field applications (medical technology or particle accelerators).

In this article, we first present some important aspects for understanding the current landscape of superconductivity (principles, materials, and barriers to applications), and then a review of the State of the Art of the applications, in any state of maturity.

2. Superconductivity principle

Superconductivity corresponds to a certain "phase ordering" that is broken, in addition to temperature, when the transport current in the superconductor exceeds a specific value I_c (critical current) or the magnetic field around the material is higher than a concrete value, B_c (critical magnetic field).

As an example, Fig. 1 represents the superconducting state diagram of the so-called YBCO, a well-known and widely used superconductor with chemical formula $YBa_2Cu_3O_{7-x}$. It can be observed that at 77K, which is the temperature of an open bath of liquid nitrogen (L-N_2), a YBCO superconductor can carry more than 10^6 A/cm^2 in the absence of a magnetic field or withstand more than 15 T in the absence of electric current.

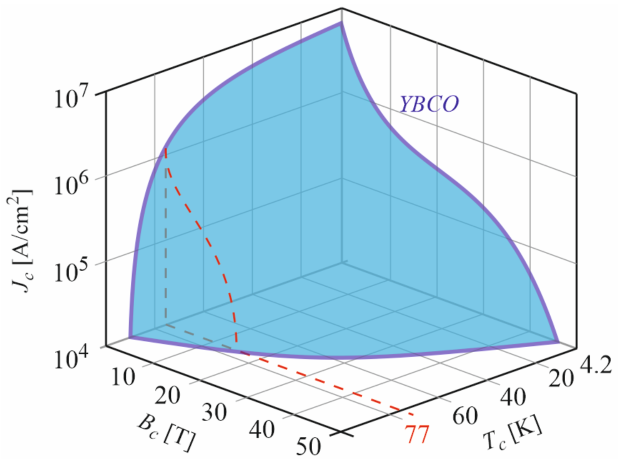

Fig 1. State diagram *BJT* of YBCO. The surface marks the limits of the superconducting state of YBCO.

Superconductors can be classified according to the critical temperature as *low temperature superconductors* (LTS) and *high temperature superconductors* (HTS).

The first category includes the materials with critical temperature lower than 4.2K (liquid Helium - temperature). The second one include

The number of materials showing superconductivity is very big, but only a few have been useful for applications.

3. Electrical applications

A. Power transmission and Distribution

One of the most promising applications of superconductors is in power transmission and distribution. Traditional power lines present resistive losses, leading to a limit on power delivery. Superconducting cables, on the other hand, can transport electricity with zero resistance, significantly reducing energy losses. Some key benefits of superconducting power lines include:

- *Increased efficiency:* Superconducting cables can carry large amounts of current with minimal energy loss.
- *Reduced infrastructure requirements:* Superconductors can transmit higher power densities, reducing the need for large transmission towers.
- *Enhanced grid stability:* Superconducting fault current limiters (SFCLs) help protect power grids from sudden surges and fluctuations.
- *Opens the possibility of distributing electrical power using low voltage DC lines.*

Pilot projects in China, Germany, Japan, or the United States, among others, have demonstrated the viability of superconducting power cables for power grids and long-distance transmission [3].

As an example, Fig. 2 shows the prototype built by Nexans, ICMAB-CSIC, Tecnalia and UAB [4].

Fig. 2. Medium voltage superconducting power cable (Endesa *Supercable* Project, 3.2 kA, 138 MVA) [4].

B. Superconducting Magnets

Superconducting magnets are widely used in several high-tech applications due to their ability to generate extremely strong magnetic fields with acceptable power consumption, impossible with conventional technologies. Some of these applications are:

1) *Magnetic Resonance Imaging (MRI).* MRI machines use powerful superconducting magnets to produce magnetic fields high enough to excite the different cellular tissues and return a high-definition image of these. The magnetic flux density required to excite cell molecules is approximately 4 T, which can only be achieved with much higher currents than those allowed by conventional technology.
2) *Particle Accelerators.* Facilities, such as the Large Hadron Collider (LHC), that utilize superconducting magnets to drive and accelerate charged particles at near-light speeds. These magnets provide the strong and stable magnetic fields necessary for the study of particle physics.
3) *Magnetic Levitation (Maglev) Trains.* These vehicles use superconducting magnets in combination with the diamagnetic ability of superconductors to create a levitation effect., eliminating friction and enabling high-speed travel. Countries like Japan and China have invested in superconducting maglev technology, achieving speeds exceeding 600 km/h with reduced energy consumption. Fig. 3 show the best-known maglev in service, which connects the city of Shanghai with its airport.

Fig. 3. Shanghai maglev. It was the first commercial train installed in Shanghai (China). In service since 2004.

C. Superconducting Fault Current Limiters (SFCLs)

SFCLs are one of the most interesting applications of superconductors in power grids. They provide protection against sudden short-circuits in the lines. Unlike conventional circuit breakers, SFCLs are invisible (zero impedance) in normal operation of the protected line and their impedance almost instantly increases in the face of excessive currents, preventing damage to the electrical infrastructure.

There are two basic types of SFCL and some variations on their configurations. The basic types are:

1) *Resistive SFCL.* It consists of (see Fig. 4a) a superconducting branch in series with the line to be protected, and calculated to transit when the current in the line reaches the maximum allowable current I_{max} (i.e., $I_{max} = I_c$). In this moment, the null resistance in the superconducting element becomes in a high resistance that reduces the abnormal current.

2) *Inductive SFCL.* It uses the perfect diamagnetic property of a superconducting screen to shield the ferromagnetic core of a reactor from the magnetic field created by a coil (preferably superconducting, too) in series with the line to protect (see Fig. 4b). The coil is calculated to create the critical magnetic field of the screen, B_c, when the current in the coil (in the line) reaches I_{max}. The screen then becomes paramagnetic, and the core is magnetized causing the element to exhibit a high inductive reactance that reduces the abnormal current in the line.

The resistive SMES main problem is that when the critical current is reached, the transition to the normal state begins at the weakest points of the superconductor, causing excessive heating that can destroy the tape.
To avoid this problem, the authors have proposed a hybrid, inductive-resistive system (I-R SFCL), in which the resistive stage is placed in the path of the magnetic field of the inductive stage [5]. The coil of the inductive stage is sized to transit with $I_{max} < I_c$, and create after transition a magnetic field $B > B_c$ in the core, being I_c and B_c the critical parameters of the superconducting resistive stage. The resistive stage then transits homogeneously, as it is immersed in a magnetic field greater than its critical magnetic field B_c before reaching its critical current.
The prototype currently under study can be seen in Fig. 5.

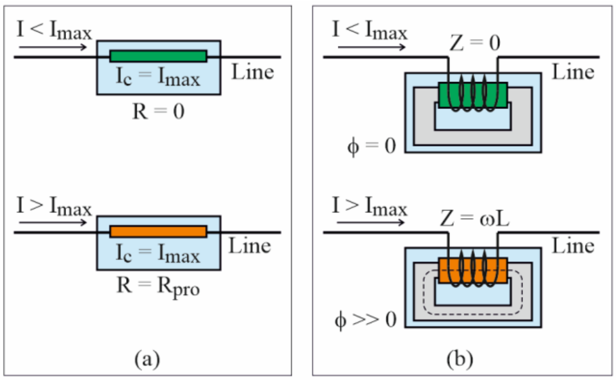

Fig. 4. SFCL basic types before and after a limiting operation. (a) Resistive SFCL. (b) Inductive SFCL.

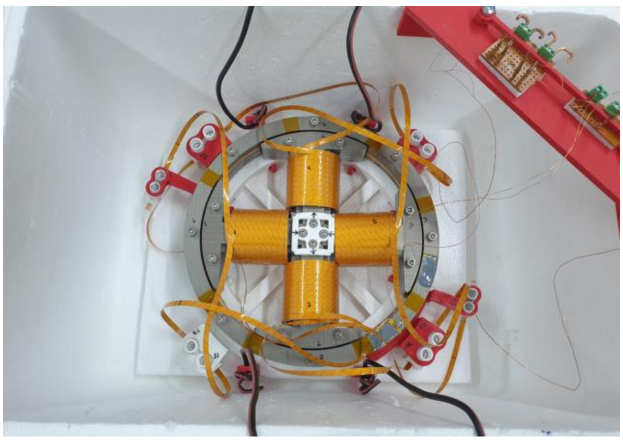

Fig. 5. Prototype of the I-R SFCL under study. The poles house the inductive stage (4 sections). The resistive stage is located right between the poles and the outer ring [5].

D. *Superconducting Generators and Motors*

Superconducting materials have enabled the development of high-efficiency electrical generators and motors. These machines offer significant advantages in:

1) *Wind Power Generation.* Superconducting generators in wind turbines increase efficiency, reducing weight and improving energy output. As an example, Fig 6 shows the first prototype in the world of a 2MW class superconducting generator for medium power wind turbines It was developed in Spain [6].
2) *Naval and Aerospace Applications.* Superconducting motors are being studied for providing compact, efficient and powerful propulsion systems in ships and aircraft, reducing the current carbon footprint. The possibility of reducing the weight and volume of the electric machines makes this technology of great interest also in the power generation plant of these vehicles.

Fig 6. First 2MW class superconducting generator for medium power wind turbines [6].

E. *Superconducting Energy Storage Systems (SMES)*

Superconducting Magnetic Energy Storages (SMES) store energy in the form of a magnetic field within a superconducting coil that carries a constant current in short-circuit as sketched in Fig. 7a. This current remains without losses thanks to the fact that the coil has no resistance. The energy storage in the SMES is:

$$W = \frac{1}{2} L I^2$$

When the grid need energy, the terminals of the SMES are connected to the line and the current injected to the line (Fig. 7b).
The main properties of SMES are:

1) *Rapid energy discharge.* SMES systems release stored energy almost instantaneously, making them ideal for stabilizing power grids.
2) *High efficiency.* Unlike batteries, SMES systems experience negligible energy loss, ensuring efficient power storage and retrieval.

3) *Longevity.* With no chemical degradation, SMES systems have a much longer useful life compared to conventional energy storage technologies.

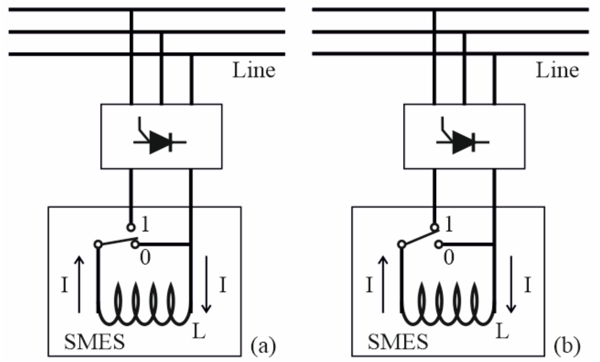

Fig 7. (a) SMES charged. (b) SMES exchanging energy (storing or delivering).

The main withdraw of SMES is the low energy density. Comparing with electrochemical batteries, the volume of a SMES with the same capacity can be about 10 times larger than that of a battery [7]. For this reason, one of the current research objectives is the design of hybrid storage systems in which the SMES shares storage with other systems, usually batteries. In these systems, the SMES is sized to absorb sudden variations in demand, relieving the battery of this stress that reduces its useful life.

F. Other applications

Other applications of interest, not specific to electrical engineering but somehow related to it, are the following:

1) *Superconducting Quantum Interference Devices (SQUIDs)* are extremely sensitive magnetometers used to detect extremely small magnetic fields. They find applications in medical diagnostics (e.g., brain activity measurements), geophysical surveys or fundamental research in physics experiments requiring precise magnetic field measurements.
2) *Superconducting Computing and Quantum Computing.* Superconductors play a critical role in the development of next generation computing technologies. Quantum Computers Superconducting qubits, the building blocks of quantum computers, enable revolutionary computational speeds for complex problem-solving. Companies like IBM, Google, and D-Wave are investing heavily in superconducting quantum computing research.
3) *Superconducting electronics.* Josephson junctions are used in superconducting logic circuits, enabling ultra-fast and energy-efficient commutation.

G. Challenges in superconductivity

While superconductors offer immense potential in electrical applications, several challenges must be addressed for widespread use. The more important ones are:

1) *Cooling requirements.* Superconductors require extremely low temperatures. The so-called High Temperature Superconductors (HTS) present a critical temperature of about 90K, being necessary the use of cryogenic systems that increase operating costs.
2) *Mechanical limitations.* Current HTS (based on rare earth cuprates), are expensive and difficult to handle for making electrical devices, as cables or coils.
3) *Costs*. Although the price of commercial super-conducting materials is gradually decreasing, it is still expensive. Reducing the prices is both a technical objective (decreasing costs) and a commercial objective (increasing demand).

4. Conclusion

Superconductors offer immense potential in electrical applications, due both to the absence of resistance when electric current flows, and to the total repulsion of the magnetic field inside them. In addition to improving the performance of electrical systems built with conventional technologies, superconductors have made possible several applications that are not possible with those technologies. and have opened new expectations for others, offering the possibility of reducing losses, increasing the capacity of the managed energy and reducing the weight and volume of the equipment. As research continues, advances in superconducting materials and technology are expected to reduce costs, and unlock new possibilities in energy and other scientific fields.

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