Review of applications of superconducting magnetic energy storage (SMES) to power systems

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Date: 01/11/2021

Abstract

A critical review of SMES has been conducted through highlighting the main contributions on power quality enhancement and system stability. Then, we can find applications in several industrial applications such as: UPS, SFCLT. SMES has been applied in these applications because they have required fast charging to compensate their demand as quick as possible. Also, its efficiency is approximately 95% which is higher than other secondary storage technologies. Through comparison with other technologies such as: *batteries* or *supercapacitors*, it's difficult to choose the suitable storage element unless pros & cons of each of them is shown. Thus, Ragone plot is illustrated for identification of their optimal regions & limitations. Basically, ESDs are classified according to function & form. This means that most of storage elements are not used for the same purpose. Some of these technologies are dedicated for energy management. Other functions are relevant to power quality improvement & reliability. Furthermore, a comprehensive assessment for several ESDs is implemented by indicating the applicable or developed technologies & other options which is not applicable or have some limitations because of its cost or other technical challenges. In addition, SMES development over the last century is investigated using different superconductive materials "ex: YBCO, BSCCO, MgB_2". In contrary, an extensive study of these materials is accomplished through presenting their applications, advantages & their challenges. Thus, a proper selection of appropriate material for magnet design is implemented according to the required characteristics. Hence, different SMES topologies & their control methods are discussed, in details, by showing the equations, that govern its behaviour during operation. Furthermore, different storage modes: charging, discharging process; managing SMES operation & identifying the power flow direction from/to SMES. If SMES is charged, the power flow is directed from grid to SMES. In contrast, SMES releases its stored power when discharged. Generally, VSC is much favourable for their simple configuration & lower switching losses compared to CSC. Finally, an economic assessment for SMES system is conducted to derive the main parameters affecting its total cost & the cases in which SMES can be profitable. On the other side, SMES cost is analysed, with help of diagrams and graphs, by assigning the cost proportions of its components with respect of the total SMES cost. Several hypotheses are made relevant to few prominent economic indicators "i.e., NPV". Such an indicator is used for determination of its cost-effectiveness. Finally, a case study has been demonstrated in which SMES is applied for transmission power capability enhancement.

Acknowledgment

I cannot express enough grateful meanings and thankful to all my supervisors who helped me during my postgraduate study to achieve high knowledge & acquire professional skills. I wouldn't forget anyone who support me during this journey.

First of all, I would like to thank my family for all the continuous support & motivation through several years of study. Without their financial help, i couldn't be able to complete my study abroad. Furthermore, I would like to show my gratitude to all member of staff that contributed to this research study & deployed time for making this work honorable & elegant.

Thanks to Prof. Weijia Yuan for his regular guidance & motivation through several periods of my study. Without your support, this work might not be released with a professional format. In addition, the guidance of Prof. Graeme Burt during, last year, is not negligible since it shaped my thoughts about the critical study & illustration of research methodology & technical knowledge. His support & guidance have added encouragement towards enhancing my research skills and completing the degree.

Additional support has been presented by Prof. Min Zhang for teaching & sharing her knowledge in superconductivity during the launch of this project.

The results of this study should be addressed to my supervisors. On the other hand, i would like to thank Prof. Derrick Holliday for his supplementary support in different aspects during this project. I cannot also forget the academic help presented from Prof. Khaled Ahmed in some parts of my study.

Thanks for all the rest of academic staff that helped me during my study in University of Strathclyde. Special thanks to Miss Lynn Gilmour & Elaine Black for their support & answering all queries related to registration for the degree, accommodation and integration in the engineering community.

Thesis Review

This dissertation is formatted to fit in an MPhil report. An extensive review of SMES solutions; for power system stability, is presented. Compared to the previous report, this report is more focused on different applications where SMES can be applied. However, a critical comparison is also made for different storage technologies to analyse the advantages & drawbacks for each of them. Thus, chapters 1 & 2 describe, in general, SMES applications and classifies each of available technologies. On the other hand, chapter 3 focused on SMES components & different used superconductors in practical applications. Conversely, a distinguishable comparison, for these conductors, is illustrated for showing several benefits of their employment. In the previous thesis, this comparison is not included. Then, it's updated to form a comprehensive report of SMES technology & its features. In chapter 4, PE devices are included by definition of several converters. Different types are shown by means of graphs & equations. An example of SMES storage response with time is eliminated because it's not the main objective of our discussion. However, this example proves the fact that the internal resistance of SMES could affect the storage power when its resistance is kept minimum. Furthermore, a general description of each converter is made for showing the integrated PCS device advantages & suitable solution for integration with SMES. This will also have an effect on the power flow from/to SMES. In addition, the system's efficiency will be affected according to the selected converter device. Then, this part is kept for concluding the importance of PCS on SMES operation. In the previous edition, SMES is integrated with IM & a 3 phase-fault is introduced for assessing the effect of SMES on fault clearing and keeping the motor in operation mode. Effectively, this part is eliminated because it's not considered as an application where SMES could be implemented. In other words, there are some solutions which can be configured for protecting the motor in these critical faults. Finally, the last chapter evaluates the techno-economic performance of SMES system. This chapter is divided in two main parts. The first part concerns the determination of some economic concepts such as: capital cost and assigns SMES components portions with respect to SMES total cost. Then, some additional sections are added such as: equipment's cost. The second part concerns the possible revenues that might result from SMES employment. This is illustrated by mentioning the influential players in RES market and comparing between SMES & reactive compensators, economically. In fact, it is difficult to estimate, accurately, the total investment cost for the project because the uncertainty of variables over which SMES is dependent. Then, it's better to estimate these costs according to the system's need.

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Nomenclature

IPP: Independent Power Producers

TLs: Transmission Lines

FACTS: Flexible AC Transmission Systems

SMES: Superconducting Magnetic Energy Storage

LP: Linear Programming

STATCOM: Static Synchronous compensator

SFCLs: Superconducting Fault Current Limiters

SMES: Superconducting Magnetic Energy Storage

UPS: Uninterruptible Power Supply

NEDO: New Energy and industrial technology Development Organization

FESS: Flywheel Energy Storage System

BESS: Battery Energy Storage Systems

CAES: Compressed Air Energy Storage

ESS: Energy Storage System

PS: Power System

EV: Electric Vehicles

HEV: Hybrid Electric Vehicles

Na/S: Sodium Sulfur

SOC: State Of Charge

ESR: Equivalent Series Resistance

SC: Superconducting Coil

PCS: Power Conditioning System

CG: Cryogenic Generator

ESDs: Energy Storage Devices

HTS: High Temperature Superconductor

MPPT: Maximum Power Point Tracking

Nb_3Ge: Niobium Germanium

HTS: High Temperature Superconductors

Nb_3Sn: Niobium-Tin

NbTi: Niobium-Titanium

LTS: Low Temperature Superconductors

BSSCO-2212: Bi2Sr2CaCu2O8 (Bismuth-strontium-calcium-copper-oxide)

BSSCO-2223: (Bi, Pb)2Sr2Ca2Cu3O10 (Bismuth-strontium-calcium-copper-oxide)

YBCO: $YBa_2Cu_3O_7$ (Yttrium-Barium-Copper-Oxide)

REBCO: Rare-earth-barium-copper-oxide

MgB_2: Magnesium Diboride

AMSC: American Superconductor

SEC: Sumitomo Electric Company

SS: Stainless-Steel

PIT: Powder-In-Tube

MTS: Intermediate Type of Superconductor

CU: Control Unit

LN$_2$: Liquid Nitrogen

MLI: multi-layer insulation

VSC: Voltage Source Converters

CSC: Current Source Converters

PCS: Power Conditioning System

THD: Total Harmonics Distortion

HESS: Hybrid Energy Storage System

DDC: Dynamic Droop Control

DAB: Dual-Active Bridge

NPV: Net Present Value

ROE: Return On Equity

EPRI: Electric Power Research Institute

STOR: Short-Term Operation Reserve

SR: Spinning Reserve

Chapter 1. Introduction

This chapter introduces the main problematic of research and discuss existing solutions for these challenges by enumerating the recent applied technologies in real projects. To do this, it is necessary to indicate the research objectives and general methodology for the study, under consideration.

1.1 Thesis Background

The power industry faces plenty of barriers including diversification of energy sources, “Nuclear, Renewable, Thermal, etc.”, deployment of expensive equipment and integration of new sub-stations to the national grid [1]. However, energy producers must obey the new rules adopted by EU commission regarding the climate & energy package. EU has put in place the climate and energy policy; referred to the package, for achieving its targets for 2030. This implies the total reduction of Greenhouse Gas (GHG) emissions to 40% below their 1990 levels, growth of the renewable energy share to 27% & expansion of energy efficiency by 27% respectively [2]. Additional effort is made to develop the grid infrastructure for accommodating new renewable sources. Consequently, this will reflect the grid stability & reliablity [3]. Following EU package, the infrastructure modernization is recommended, nowadays, to cope the environmental pollution, resulting from thermal sources (coal, fossil fuels) for electricity production. Thus, self-generation is also encouraged, in many households, for achieving additional power reserves in the grid & reassuring the usage of green sources “Self-generation & green sources reliability”. This proposition will permit several users to become Independent Power Producers (IPP) that will have a massive reflection on the European grid reliability & will allow several countries to export/ import power in case of power surplus/deficit [4]. Many challenges stem from the growth of energy demand worldwide. According to the US department of Energy report, electricity demand in the U.S have increased 2.5% annually over the last 20 years [5], [6]. This recommends a huge supplementary energy to cover the need for the majority of regions. In 2020, the total energy demand would reach “**27,000 tWh**” ~ 75% more than the energy demand in 2000[1] [7]. Moreover, U.S projections have affirmed a moderate growth from 3.9 billion kWh in 2010 to 4.7 billion kWh in 2035; an increase of 20% [8]. It is strongly agreed to include the most significant faults, due to instability, in the grid as follows [1], [9]:

a) Voltage sags
b) Frequency oscillation and harmonic issues
c) Phase Unbalancing

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[1] The total energy consumption is approximately 13,200 TWh by 2000.

d) Grid Hierarchical Topology (the existing grid may suffer from a dominant failure if one element is damaged or shut-off for any purposes).

Generally, power system stability is essential to keep a nominal operation for the grid. However, a loss in transmission line or generator can result in growing oscillations that need to be damped using appropriate equipment. As a rule, the grid experiences losses through transmission lines that were estimated by 8% of the total generated electricity [1], [7]. This portion reflects an impressive economic loss since power losses reduction is accounted as an economic advantage especially that the transmitted power is in range of “MWs”. Due to these losses, a non-optimal operation for power transmission network & total system collapse is undergone. Traditionally, these challenges are diagnosed by the installation of Flexible Alternative Current Transmission Systems (FACTS) devices. Other technologies are recently developed for solving the associated challenges of network collapse such as Superconducting Magnetic Energy Storage (SMES). This technology is used due to its capability for modulating real & reactive power. In addition, it helps on providing voltage support, with assistance of power electronics devices, in case of voltage dips occurrence in the system. It must be denoted that the maximum allowable voltage dip should not exceed 25% and cannot last more than 20 cycles [10]. In contrary, a restoration of power flow, after fault clearing, might result in an instability at both frequency & voltage in T.L, FACTS-SMES device is proposed to stabilize the system’s frequency since this storage system helps FACTS to improve its performance & compensate the required active & reactive power. In contrast, the addition of new power sources leads to excessive currents on the main T. L’s. Thus, the grid infrastructure should be designed to accommodate additional sources or TLs to prevent a dynamic voltage instability. This phenomenon usually occurs when the grid is loaded by various generators. As a result, the voltage gradually decreases leading to a total voltage collapse. Then, superconductivity can find application in these critical issues by affording enough capacity in transmission lines until the main generators/ lines are back on-line [10]. Despite that, different methods are recently suggested to minimize TLs losses by adjusting the control variables: tap position of transformers & reactive power injection of VAR generation sources. Effectively, these methods are used for stabilization of system’s voltage profile. Linear Programming (LP) technique is applied to obtain an optimal solution leading to a minimum power loss. Several models are explained using different mathematical equations: showing the correlation between tap-changing of transformer & voltage profile on a specific bus. Nevertheless, this accounted as an exhausted model. Then, the computation time would be too long for achieving the objective function.

This method has been tested on the 6 & 39 bus systems and the TLs losses are attenuated 44% after N number of iterations. However, high number of iterations represents a barrier to expand that solution widely [11]. Then, another study is conducted to show the effect of Static Var Compensator (STATCOM) on total reduction of TLs losses & improvement of the voltage stability for a transmission system. A load flow study is implemented using Newton Raphson algorithm which determines the critical points on a given system. Based on this analysis, the optimal regions for STATCOM placement are selected. Thus, this study is very beneficial when the objective is only the reduction of line losses or reactive power injected to the TLs. Nonetheless, this solution is impractical because STATCOM device is economically infeasible. Generally, reactive power compensators are very efficient to deal with voltage instability or TLs losses. Regarding several types of faults that might exist in transmission line, three-phase fault has to be cleared in few seconds. Conventionally, fuses have to be replaced after one-time use. This urges to find another equipment that fulfils the same objective with low cost. Then, resistive type Superconducting Fault Current Limiters (SFCLs) are introduced to prevent such a damage in TLs. These limiters can recover, after fault, quickly & keep normal operation for the electric grid. SFCLs act as a high resistance in case of excessive current to limit its value to permissible ranges, per shown in Figure 1 [12]. Even, superconducting cables are primarily installed; instead of normal conductors, for minimizing the grid's losses. In this paper [13], a thorough modelling of current limiting performance for SFCL has been explained.

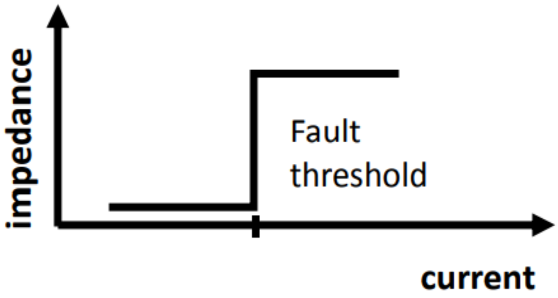

Figure 1- SFCL working regions during steady state & fault conditions

1.2 SFCL performance

- **SFCL prototype**

In Figure 2, the proposed prototype consists of 16 elements connected in series. Each element includes four superconducting tapes and an external 180 mΩ shunt resistor. The selected tape is American

Superconductor’s 344S. The total length of the superconductor is 25.6 m. COMSOL is dedicated for building up 2D finite model of SFCL.

Figure 2- A modular SFCL consisting of 16 elements; each containing 4 YBCO tapes of 0.4 m length with shunt protection [14]

- **Circuit model**

In the following circuit model, SFCL is considered for testing its capability to limit fault currents, reaching up to kA values. Several fault currents were applied between 1 and 7.4 kA [14]. As shown in Figure 3, the system consists of: 3 MVA/15 kV/380 V transformer, main switch, SFCL prototype, variable resistors R1 & R2 and a switch for short circuits. These resistors are controlling the pre-fault current to permissible values ~ 300 A. Meanwhile, the fault current is only driven for five cycles. Based on [13], SFCL is capable to limit fault currents in range of 350- 420 A which can be sustained by circuit components.

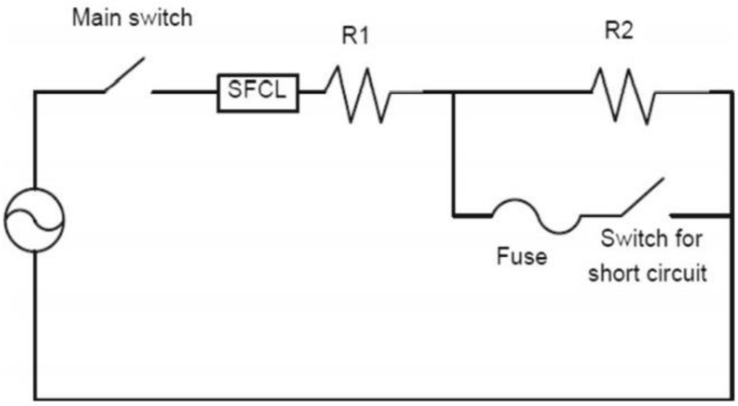

Figure 3- Circuit model for fault experimental system [13]

- **Design Parameters of SFCL**

During normal operation of the grid, SFCL remains off-line since the electrical current is within the permissible range. In case of faults, this element operates to mitigate the high current that may cause serious problems for different components in the grid. They can be used, for instance, in the distribution grid with phase voltage U =20 KV and the current is limited to 100 A. Consequently, the resistance required for limiting the current ~ 200 A. Hence, the superconducting tape that is acquired for current limitation equal to:

$$L_{tape} = \frac{Rlim}{RAg} \tag{1}$$

Thinner Ag layer is inserted as a stabilizer (see Figure 4). However, at a tape resistance of 1.5 Ω/m, the specific power released after the fault is given by:

$$P= R_{Ag} * \frac{Ilim^2}{Wtape} \tag{2}$$

From [15], it’s advised to develop a particular arrangement housing the superconducting tape, for a specific length, to maintain its working temperature below its critical levels & safeguard their electrical & mechanical properties. A complementary cooling system is mandatory for SFCL design to prevent the thermal leakage & dissipated heat; resulting from irreversible magnetization of superconductor. As would be discussed in next chapters, this cryogenic system is highly affecting the cost of system.

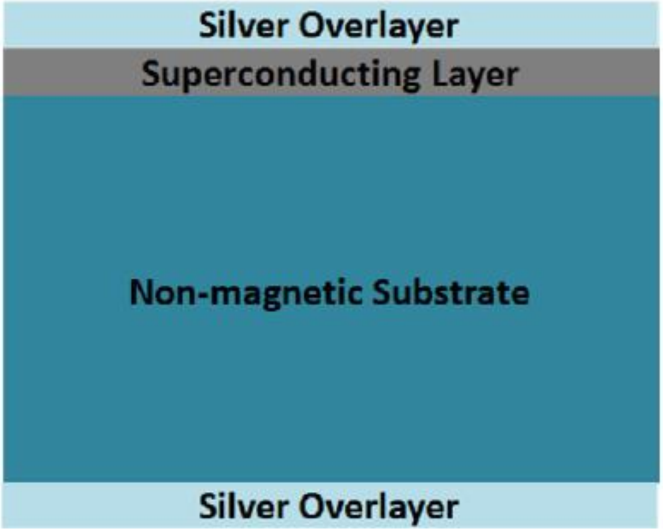

Figure 4- A cross section for stabilizer-free tape

1.3 Literature Review for SMES contribution on Power system applications

- **Development of UPS-SMES unit**

Due to distinguished advantages of Superconducting Magnetic Energy Storage (SMES) in industrial applications, research has been conducted for testing its capability on protecting Uninterruptible Power Supply (UPS) from momentary voltage drop & power failure. Toshiyuki & his colleagues have demonstrated in their published paper that Low Temperature SMES can be cost-effective while incorporated with UPS system due to its high energy storage capability in a very short time. This project is being part of the research program adopted by the New Energy and industrial technology Development Organization (NEDO). UPS-SMES module is basically configured to provide the required energy, to the load, through AC/DC converter when a power failure / momentary voltage drop occurs. The selection of Superconducting coil is an additional obstacle due to merits associated with existing alloys. Two different materials “Nb-Ti”, “Nb_3Sn” are compared in terms of mechanical properties, cost, size. The appropriate alloy used for this application is Nb-Ti since it is cost-effective and has a lower size compared with other compounds. Furthermore, a critical design for the coil conductor has been implemented with a proper choice of NbTi/Cu compacted strand cable. The discharge process of SMES is, approximately, following a linear shape.

The stored energy in SMES is reduced to half of its initial value which corresponds to 30% drop in the coil current from 1000 to 700 A. After the illustration of the corresponding relation between coil current discharge & stored energy in SMES. The study of the optimum values for the current density & the allowable magnetic field under pulse operation is presented, thoroughly, by demonstration of AC loss equation for the conductor. These parameters are highly sensitive to the magnetic field & temperature of the coil. Any rise in either of them might quench the coil & then SMES can lose its superconductivity. Relative relation between coil inner radius & SMES stored energy is proportional which means that the increase of the inner radius of the inductor, under the assumption of a fixed conductor length, affects the storage capacity of the inductor. However, the coil inner radius limit is restricted based on leakage magnetic field & conductor stress limits. Thus, the selection of appropriate value might cause a problem since multiple variables are overlapped. These, optimum values can be obtained upon the application requirement. At the end, a comparison has been made between the twist winding & flat winding for demonstrating the best method to use for these applications. Then, twist winding has a reduced AC loss since its max temperature after the pulse operation is still lower than flat winding. In addition, the corresponding max. temperature for the flat winding results in the coil quench which means that this method is not suitable for SMES-UPS unit. Then, the twist winding is suggested for that reason [16].

1.4 Research objectives

Nowadays, the reliability of RES in the grid network becomes vital to get rid from the negative consequences of conventional sources for power generation. Also, this will maintain the pollution levels to reduced levels. In a microgrid scheme, several decentralized power sources are integrated to fulfil the demand for various loads. Although their variety & efficiencies, few loads couldn't be supplied unless a secondary storage technology is connected. This situation critically appears when a fault occurs or some generation sources are out of service. Thus, the upcoming search for another storage element is suggested for this purpose. Superconducting Magnetic Energy Storage (SMES) is introduced for that case due to its fast response & high efficiency. As discussed previously, this technology is specifically developed for solving stability problems & power quality enhancement. Before SMES introduction, a brief comparison is illustrated between superconducting storage technology & other storage elements: battery, supercapacitors, etc. This is an elementary task before going in-depth in technical specifications of SMES & their different topologies. This can be implemented through illustrating the pros & cons of each storage technology and their points of strengths & weaknesses. However, the main objective, of this report, concerns SMES development & its effects on power system applications. Generally, a techno-economic assessment for such technology is impressive for determining its effectiveness in different applications. This will also help for optimization if this is required in several projects. Then, a cost assessment for SMES is presented, at the end of the dissertation, to evaluate the profits from that technology.

1.5 Thesis Structure & Methodology

This report structure helps on identifying the main objectives for each chapter & the correlation between them. It is useful to conclude the aim of this report by defining this global framework of the thesis. This structure encompasses the followed methodology, in the dissertation to provide a general review on SMES applications in the industry & critical challenges associated with its integration. In Figure 5, a general methodology is conducted for SMES applications by acknowledging the significant contribution of SMES techniques on solving power quality problems, voltage instability of the grid. A precise comparison, between different storage technologies, is a first step to evaluate the significance of SMES technology. Then, SMES is analysed in terms of components, control system & cryogenic parts. Several applications are included to prove the effectiveness of SMES for solving critical problems in the grid. At the end, a cost evaluation for SMES systems is highlighted.

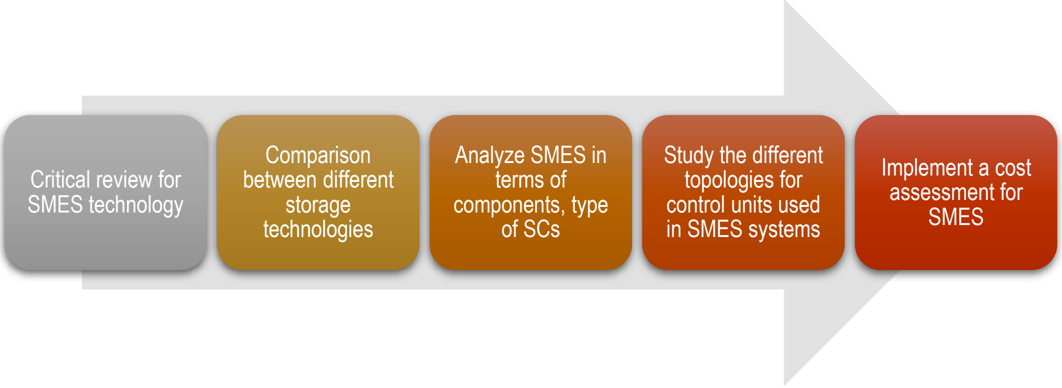

Figure 5- Principle elements forming the structure of the dissertation

Additional task of finding correlation between chapters is suggested for finding the common objective. This can be illustrated, as shown in Figure 6. Since the first chapter concerns a state-of-the-art for different applications where SMES is convenient. So, the correlation between it & other chapters (2,3 and 4) exists. Despite this, most of these chapters didn't find a coherent bond with 2nd chapter because the latter compares between different storage technologies which is beyond our scope. In fact, this comparison is made for differentiating between SMES & other technologies from technical & economic point of view, but the main target of this report directed towards SMES utilization & its different benefits.

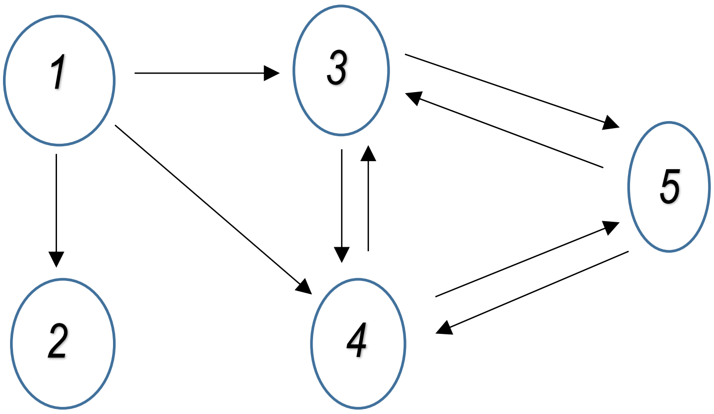

Figure 6- Correlation between chapters 1-5

In this chapter, a critical review of SMES applications is highlighted through discussing its contributions on solving challenging problems in the grid. Then, SFCL is introduced to focus on a recent technology that is mainly used as an alternative for fuses & circuit breakers. This technology has been implemented to avoid the replacement of fuses that were not designed to operate after fault occurrence. In addition to this, a summary of UPS-SMES installed unit is presented to prove the significant usage of SMES to prevent power failure or voltage disturbance on UPS system. Then, the research methodology is illustrated to represent the followed steps to achieve the adopted objectives for that dissertation.

Chapter 2. Energy Storage Technologies

2.1 Overview

Nowadays, energy storage is widely applicable in power grid due to its contribution on system reliability & efficiency through offering a spinning reserve for power stations. In addition, this advantage can be used at customer level for self-generation. Generally, it exhibits a high effectiveness for economic exploitation of energy resources. Thus, energy storage is not only an emergency solution. As a contrary, it influences the total equipment cost. Various storage devices are available for different power system applications. Most of them are sharing specific features in terms of discharge time, cost optimization, power capacity & efficiency [17]. Among multiple storage devices, only two storage technologies are based on superconductivity: SMES, Flywheel Energy Storage System (FESS). A detailed description, for each technology, will be highlighted later by discussing both advantages & disadvantages. Conversely, Battery Energy Storage Systems (BESS) are particularly implemented for voltage and frequency control. Unlike these previous features, their expensive cost has prevented its consideration for some large-scale projects [18]. Scope on these technologies is required to build up a critical knowledge about several energy storage systems. Hence, Energy storage technologies are divided into two categories:

- Short-term
- Long-term

- **Short-term storage technologies**

Short-term storage technologies include elements, that have the capability to store energy and deliver it for critical loads. These elements were designed to discharge from, at least, 1 minute to 2 hours. Their storage capacity plays a fundamental role on discharge rate. Batteries (lead-acid & advanced), flywheels (low & high speed), supercapacitors and SMES are bright examples of short-term storage devices that are assigned for different purposes. Currently, batteries have the broadest range of applications. On the other hand, SMES technology is specifically recommended for power system applications. Often, they are applied for power quality improvement. These technologies are efficient in case of transient loads behaviour [19]. However, its economic evaluation, in most of applications, exhibits an expensive cost. Although the projected cost of bulk storage elements affects their selection in different power applications, battery banks & SMES technologies are widely used due to their moderate prices, as discussed before.

- **Long-term storage technologies**

These technologies are applicable for energy system applications that lasts from 2 hours to few days. Industrial applications have used enormous storage devices that is responsible of supplying the interrupted load for a long period. Compressed Air Energy Storage (CAES), hydrogen and hydro-electric storage are used for long term storage technologies. Practically, their time response, for meeting seasonal load fluctuations, is slower than its corresponding short-term technologies.

2.2 Indicators of an energy storage system

Any Energy Storage System (ESS) consists of a device; in which a typical conversion from an energy form to another reveals. Not all storage devices are operating the same. For instance, batteries are storing electricity in an electrochemical form. However, supplementary losses exist due to auxiliary services (control, cooling, etc..). These supplementary services need more power to operate efficiently. Hence, ESS's efficiency will be reduced. Then, further study of the main influential indicators of ESS will help on the selection of the best storage device; that matches the requirement of Power System (PS) application. Then, the main influential parameters of ESS are:

- Maximum power than can be afforded or absorbed to/from the grid (P);
- Duration time of discharging (Δt);
- Number of cycles that can be sustained during the lifetime of a storage device (N);

For any storage device, there is usually a minimum quantity of energy; that must remain inside to fully control input/output power. If the storage device discharged below a certain level, an extra effort is required to control ESS. Then, the rated energy of such device can be obtained only if the power delivered (P); to the grid, for an interval Δt is given, as shown by the following equation:

$$E= E_{min} + P\Delta t \tag{3}$$

Accordingly, the efficiency of ESS in a cycle can be found through:

$$Ŋ = \frac{P\Delta t}{\frac{P\Delta t}{ŋ s ŋ c}+Pidle\Delta tidle+Paux\Delta tcycle} \tag{4}$$

$ŋ_S$ is defined as the round-trip efficiency of storage device, $ŋ_c$ is the total efficiency of converters. While P_{aux} is the power dedicated for auxiliary services & P_{idle} signifies the power loss during the idling phase. For efficient storage, lower auxiliary power & idling losses are required. In contrary, this will reflect the cost of ESS. Once, the auxiliary power is kept minimum, the size of refrigerator, needed during cooling or other equipment used for control will be minimized, affecting the cost.

2.3 Ragone Chart

Energy Storage Devices (ESDs) are characterized by the power & energy available for a typical load. Thus, the choice of an appropriate energy storage unit is relevant to the load specifications. A simplified diagram "**Ragone plot**" is introduced for distinguishing between many storage devices in terms of: "*Power density (W/Kg)"*, "*Energy density (J/Kg)"*. The following diagram is usually accounted as a guide for battery usage which determines its optimal regions and clarifies their limits of operation. From Figure 7, batteries have higher energy density compared to capacitors. In contrary, capacitors are distinguishable for its high-power density (W/Kg). Then, batteries are suggested with long-term applications (>100 s). Practically, a storage facility can be built up, rated to MWs, based on large-scale batteries. Furthermore, batteries can afford a continuous supply for few hours in a small-scale. Thus, it is recommended in various industrial purposes. On the other hand, capacitors are suitable for short-term applications (<0.01 s). Their higher power density allows a quick discharge of its stored energy while they are not designed to store massive energy per unit mass or volume. Thus, their energy density is considered low.

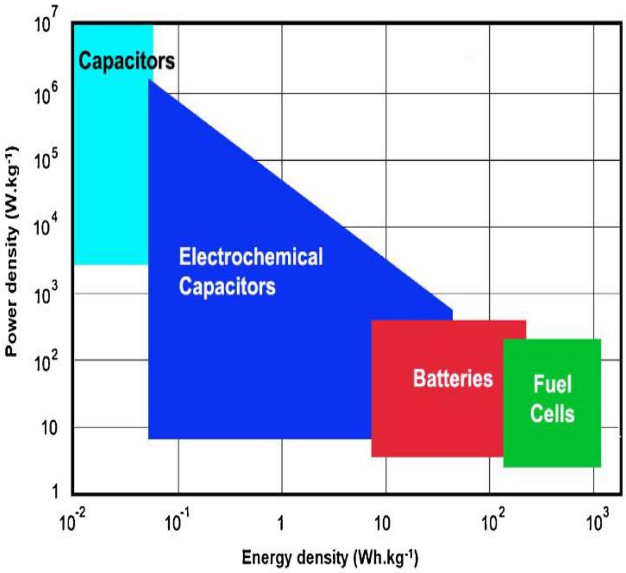

Figure 7- Ragone Chart: power density as a function of energy density for several ESDs [69]

2.4 Batteries

Electric batteries are broadly used for many power applications. Basically, they are devices which store electrical energy in electrochemical form through activation of electrochemical oxidation-reduction reaction or a physical reaction. Two prominent characteristics are distinguishing battery systems: operating voltage, maximum current capability. Then, they are placed with several configurations "series" or “parallel” arrays to obtain the desired power. Batteries are primarily used as an effective tool for power balance. For grid connection, an intermediate power conversion is required to match AC loads. Hence, an inverter is connected between batteries and the grid. Typically, there are two valued types of cells: primary & secondary. Primary cells are designated for one time usage only. These cells are compatible with small-scale applications and rarely used in large-scale applications. In contrary, secondary cells might be re-used several times. In this context, it is essential to indicate that secondary cells are re-chargeable[2]. The latter is widely employed in industrial applications. Generally, Most of BESS are based on a mature Lead-acid & Nickel-cadmium battery technologies. For grid applications, Lead-acid technology is highly recommended. It is frequently used for load levelling in power distribution systems. Lead-acid technology is effective, reliable and robust choice for an optimized economical assessment. However, its weight is of little concern. These batteries are also installed in distribution generation systems, automotive applications & UPS devices. Furthermore, it provides a back-up generation, when considering of small wind or solar installations. This technology is promoted due to its efficiency; which can reach up to 85%. As a rule, battery’s efficiency depends on temperature & duty cycle. Although that, it is stable over a specific range that cannot exceed 15%. Moreover, its lifespan is limited because cells are discharging themselves over time. This drawback presents a challenge if those cells are effectively used in industry, so that the total cost of the system will become expensive. Thus, long lifetime cells are ultimately preferrable to avoid the replacement of energy storage equipment [20]. On the average, lifetime for majority of cells, utilized in industry, is approximately 15-30 years. Battery **power density**[3] is a preliminary indicator to select the best technology for a specific application. Although the specific features of lead-acid batteries, manganese and phosphate-based lithium ion shows excellent performance as shown in Figure 8. Hence, battery cells lithium-ion based are used in different applications such as: Electric Vehicles (EV), Hybrid Electric Vehicles (HEV) [21]. Conversely, this technology might not be useful for all applications that recommend higher energy density. Despite this, other advanced technologies are emerged into the market which have a superiority over lead-acid technology in terms of performance, handling characteristics, cost and lifetime. For instance: zinc bromine (Zn/Br) & sodium-sulfur (Na/S). The latter technology belongs to flow batteries which are tested over large scale. They are accounted as interesting devices due to its long-life time compared to secondary cells. Thus, Na/S

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[2] Secondary cells are distinct types of batteries which can be recharged by, simply, applying voltage across its terminals; so that it can be used several times for large-scale applications.

[3] Power Density (Wh/kg) is the ratio of the power available from a battery to its volume (W/litre). It indicates how much power a battery can deliver on demand. Transportation systems, medical devices and power tools usually requires higher power density for an efficient use.

batteries are widely suggested for energy storage in renewable applications. Successful use of battery banks suggests its parameters identification. Depth of Discharge (DoD) is a significant factor; that must be measured in different applications. Briefly, DoD indicates the percentage of battery's discharge relative to the overall capacity of the battery. The optimum selection of DoD will have a great impact on the battery performance. For battery specifications, the maximum DoD is selected and the user should avoid the regular usage of the energy battery more than advised by the manufacturer. Conventionally, higher DoD rates reduce the lifespan of the battery. Typically, a battery's DoD range of 60-70% is accepted for most of applications. For lead-acid technology, the DoD can reach up to 80%. The latter achievement might be thought as a breakthrough. However, various applications recommend, practically, the selection of batteries with optimal DoD to avoid the breakdown of batteries, on short term.

- ***State of Charge***

State Of Charge (SOC) is a crucial battery's parameter that is strongly reflecting the available capacity, given in (Ah), as a percentage of its rated capacity. It is considered as a thermodynamic quantity, assessing the potential energy of the battery. The identification of this parameter represents a critical challenge due to the numerous available batteries and their applications. Thus, several research efforts have worked to improve SOC estimation accuracy. In fact, SOC estimation is a significant task accomplished by energy management system. Precise SOC estimation prevents damage of batteries and strengthen its long-term performance. SOC calculation, as given below, is based on the counting of ampere hour [21].

$$\mathrm{SOC} = \mathrm{SOC}(t_0) + \frac{1}{Crated} \int_{to}^{to+\tau} (Ib - Iloss)dt \tag{5}$$

Where,

SOC = Estimated State of Charge, SOC(t_o) = the initial SOC, C_{rated} = the rated capacity (Ah), I_b = the battery current (A) & I_{loss} = the current consumed by the loss reactions

This equation shows that SOC is mathematically computed by means of measuring the current over its usage period (t_o) to ($t_o + \tau$). The accuracy of coulomb counting method is based on precise measurement for battery current and exact estimation of the initial SOC. The initial SOC can be obtained through defined initial operating conditions. An interesting issue appears in the previous equation which is losses, occurred during charging and discharging cycles.

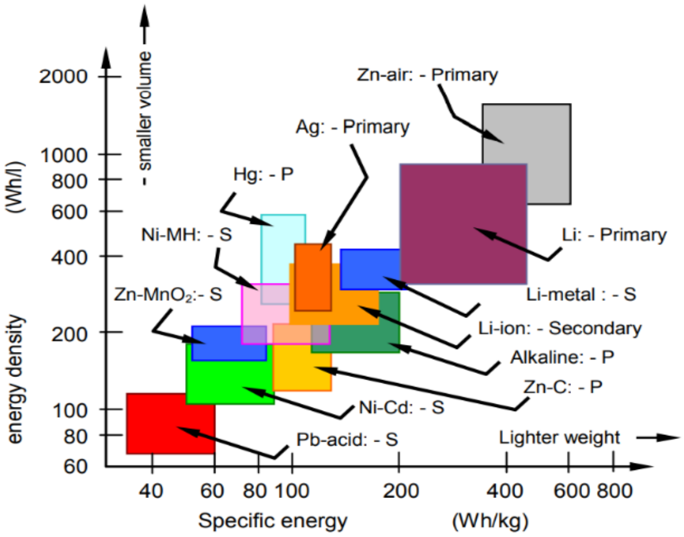

Figure 8- Power densities classification of different battery cell technologies

In fact, the released energy from the battery is lower than the stored energy. However, different types of losses usually appear during the normal operation of batteries. Self-discharging losses, Charging & discharging losses. Thus, accumulated errors tend to deviate the SOC estimation beyond the perfect value. Thus, current losses are integrated over a battery's use period, previously, for better estimation of SOC.

2.5 Flywheels

Flywheel-based systems are often used as a mechanical storage device for thousands of years. It's a simple mechanical energy storage device which stores kinetic energy in the angular momentum of a spinning mass. The amount of stored energy is dependent on the rotor speed, mass and the configuration of the flywheel. In the beginning of 21st century, it has been accepted for short-term energy storage devices in propulsion applications such as engines. Generally, they are employed for transient grid support & back-up generation during which a bulk amount of energy is delivered, for a load compensation, within a very short period (~ 10 -15 seconds); the same as SMES. It's advised that a secondary or back-up device should follow that, (i.e., diesel generator), because Flywheel-based systems is not capable to operate as a power supply for a long time. However, some of them can be designed to supply power for few minutes, hours. The average power rating of flywheels varies from 2 kW & 2 MW while the storage capacities vary between 1 to 100 kWh. For large power ratings, several flywheels are installed, in parallel, to achieve the desired output power. The prominent commercial suppliers, for such flywheels, are Pillar, Active Power and Caterpillar companies.

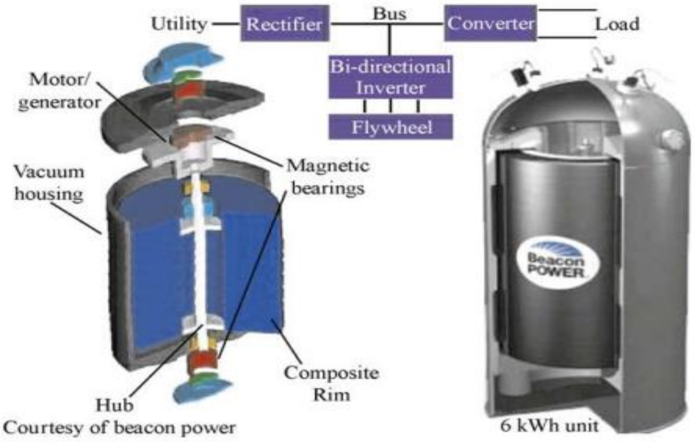

Figure 9- Schematic of energy storage wheel system

Even though, R&D's on flywheels systems is oriented towards development of machine speed up to 10,000 RPM. Regarding the operation, FESS exhibits a good performance except some losses, which result from frictional losses associated with rotor bearings. These bearings are essential elements to hold the rotor during its rotation. In Figure 9, a simple flywheel is illustrated. Vacuum chamber surrounds the rotating device; to minimize the friction losses from air. The energy can be stored in the flywheel by means of a motor unit. Compared with batteries, FESS is practically leading due to its long-life capability for affording multiple charging-discharging cycles [22]. It's mainly suggested to operate with a higher speed since it is efficient for attaining high flywheel storage capacity. The flywheel storage device has a special feature of energy delivery to the load and extracting it back by means of reversible motor-generator. This might not be the case with other energy storage devices. However, it's difficult to synchronize the flywheel generator; along the grid, without the use of AC-DC-AC converter. Briefly, the extracted energy, from the flywheels, has an adverse effect on the rotational speed of the rotor. As a result, the power output frequency, from the generator, will be variable. Then, a power electronic converter is used, for that purpose, to obtain a DC power output & then re-converted to AC output with the same frequency as the grid. According to the US department of energy, the round-trip efficiency of such systems might attain 85%-95% which makes it convenient for storage purposes. Economically, the size of this storage system is expected high because of cooling systems; required for getting rid of additional heat induced from friction losses. Unfortunately, this cannot be compromised or eliminated since it is necessary for adjusting the temperature inside the storage unit. This process is referred to "*Heat management*". The latter process prevents from an anticipated overheating that might cause damage for the whole unit. The most significant application for a flywheel is for energy restore in motor vehicle. The braking process, in a vehicle, is controlled by a flywheel device that converts the kinetic energy stored in motion into electrical energy, collected back by a small generator. Flywheels storage might be mixed with other renewable source “i.e., wind plant”. This allows wind plant to store energy if the grid is balanced. During high demand, the wind must deliver the power to the grid. Hence, a reliable and efficient renewable source is maintained through getting an affordable back-up source. As an illustration, 150 MWh FESS is constructed to provide frequency regulation for NY grid operator. This plant uses around 200 flywheel units. It can afford 20 MWh, each 15 minutes, which can be enlarged for few hours with the same unit size [23].

2.6 Superconducting Magnetic Energy Storage (SMES)

SMES is an outstanding device that allow to store electrical energy in the magnetic field, generated by DC flow of current in a superconductor [24]. Due to superconductivity, the conductor can almost exhibit no losses which avoid conductor’s damage over time. The inductor maintains its superconductive state through immersion in a coolant; liquid helium or Nitrogen, based on the required refrigeration points. A typical SMES system consists of three main components: Superconducting Coil (SC), Power Conditioning System (PCS), Cryogenic Generator (CG). A refrigeration system is necessary for maintaining the coil’s superconductivity. SMES exhibits high efficiency ~ 95 - 98% and very rapid response, few milliseconds of energy compensation. It can supply up to GWs in case of high-power pulsed loads while its power handling capability is also an impressive feature for high load requirements. Thus, SMES is proposed for real applications in utilities. Referring to Ragone theory, shown in Figure 7, SMES output is less dependent on discharge rate compared with batteries. SMES is also recommended for large-scale industry because it is designed to sustain complete cycling & continuous mode of operation since it has a high life cycle. The round-trip efficiency for large units is predicted to reach up to 90% [25]. Then, they are suggested for voltage instability cases & power quality enhancement. For instance, SMES could be integrated in a micro-scale[4] device for reducing the system oscillations; following a transmission line or generating unit loss. SMES is capable to fulfil that through injection of active & reactive power. In addition to that, it is used as a “spinning reserve” for large-scale applications, in case of generation unit outage, until the main unit is returned back to the service. SMES is very efficient for securing demand on this short time. However, it is advised to not be operated for long time since its energy density is low [24].

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[4] Micro SMES is a developed storage device which protects the customer side from entire power shutdown. Its location is definitely in the power distribution circuit. Its available power ratings are usually in the range of 1-2MVA. Such small scales are not merely used for power compensation. In addition to that, they can effectively manage the power quality in the TL line.

To tackle that issue, SMES is integrated with hybrid ESS system. Hence, the requirement of power & energy is attained through different power control methods. Unlike diesel generation or batteries, SMES is smaller, in size, than other storage ESS. Hence, optimization of system dynamic performance by continuous usage of Micro-SMES is greatly encouraged [26]. SMES technology is competitive, compared with other storage devices, due to cryogenic system's cost [27]. However, size increments of SMES, per unit of stored energy, is economically beneficial. Furthermore, Strobridge has developed a method for estimating the liquid helium refrigerator ($T_{cooling}$ @ 4.5 K) cost based on a limited number of data points.

In his study, he used the carnot ratio for scaling different refrigeration points to a unified refrigeration point which is 4.5 K. The author, in his dissertation, relies on a fact that the dollar value, in 1991, would be ultimately expensive compared to its corresponding value for the manufacture year of the cryogenic components (i.e., compressor). Thus, he refers all his hypothesis to 1991 dollars exchange rate. Then, he concluded an equivalent equation that can estimate the refrigerator cost by knowledge of the refrigeration capacity R(KW) which is limited to 0.04 to 15 KW [28]:

$$C(M\$)= 1.51\ (R)^{0.7} \tag{6}$$

The refrigeration cost is estimated around 10-15 % of SMES total cost. R value must be assumed carefully to obtain low cost for the cryostat. Thus, it's not advised to select the maximum value; unless required by the load.

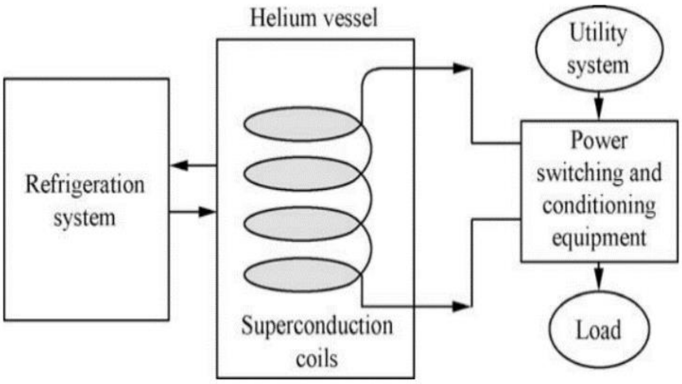

Figure 10 – Main SMES elements [67]

2.7 Supercapacitors

Capacitors are electrical devices that store energy directly in form of electrostatic charges. Simply, conventional capacitors consist of two electrodes which are parallel to each other and separated by a distance (d) by a dielectric material such as polymer, Aluminium oxide. There are several functions implemented by capacitors: RFI filtering, cascaded multilevel inverters for Var compensation and supercapacitors. Briefly, the energy stored in a capacitor, can be expressed as the product of capacitance (C) and the square of voltage across its terminals (V_c).

$$E=\frac{1}{2}C^*V_c^2 \tag{7}$$

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, are employed as ESDs for several applications. The storage technique for supercapacitors is ultimately different from other conventional capacitors. In capacitors, two metal plates are separated by a non-conduction layer called dielectric. Simply, if a current source charges any of these two plates, a charge with an opposite sign on the other plate is induced. In Supercapacitors, the energy is stored through an electrolyte solution between two solid conductors. Supercapacitors use higher space of electrodes and thin electrolytic dielectrics. These characteristics enable them to achieve higher capacitances rather than conventional capacitors. This method affords higher density & design compactness for such a storage device. They are also used in AC/DC converters where a large capacitor is installed to maintain a voltage stability across the load terminals. Furthermore, it helps for smoothing out ripples generated in the circuit. Thus, they are often integrated for grid support applications, like batteries since there is no transfer between an energy form to another. Furthermore, they can be used as a power quality device, to provide ride-through of power cut within few seconds, similar to flywheels.

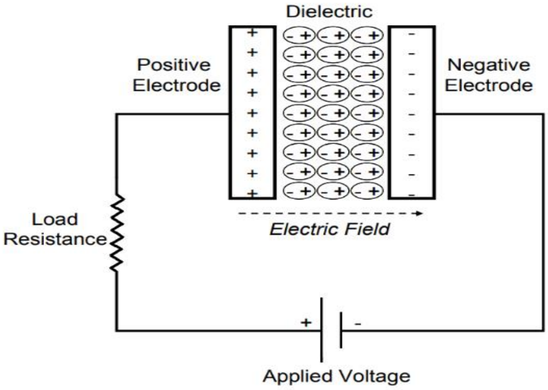

Figure 11 - A schematic of conventional capacitor

From Figure 11, the capacitor is connected in series with an external load resistance (R). Since the capacitor components (electrodes, dielectric, current collectors) are considered as part of what we have called "*Equivalent Series Resistance (ESR)*". So, the equation that govern the maximum power flow in the capacitor can be given, as shown below:

$$P_{max} = \frac{V2}{4*ESR} \tag{8}$$

From the equation above, we might conclude that ESR affects the maximum power flow in the capacitor. If the total resistance is high, P_{max} will be small. Supercapacitors are able to operate with the same principles of capacitors by maintaining low ESR. This advantage leads to a similarity between supercapacitors & conventional capacitors in their power density. Compared to other ESDs, supercapacitors have higher power density, shorter charging times and longer cycle life [29]. In contrary, capacitors have the same flywheels weaknesses of short duration supply, high power dissipation and self-discharge loss. Thus, supercapacitors are mainly developed for tackling these drawbacks by minimizing the ESR to maintain a safe operation with no overheat; that can damage the device. The main developers of capacitors, worldwide, are Power System Co. & Chubu Electric Power in Japan.

2.8 Assessment & comparison between Energy storage technologies

- **Technical Maturity**

Generally, the selection of a suitable ESD for a specific application is one of the most challenging tasks unless the application requirements are determined. In bibliography, it's rare to find an optimal ESD. Thus, a re-definition of a technical maturity of ESDs is suggested as shown in Figure 12. These technologies can be classified, accordingly, into three main categories:

- *Mature technologies:* Lead-acid battery is a famous example of a mature technology which has been used for more than 100 years. It's a reliable energy storage technology & recommended for its distinguished features (for details see section 2.4).
- *Developed technologies*: These technologies are developed & commercially available but its reliability is under consideration. SMES, supercapacitors & some battery types are technically applicable & developed. However, their integration in large-scale utilities & projects are still not expanded since current studies are taken place for further advancement.
- *Developing technologies*: Fuel cell is not a mature technology which is under development. However, it's endorsed technically & have been tested by several institutions. Extra efforts should be implemented on the economic & environmental sides for more applicability.

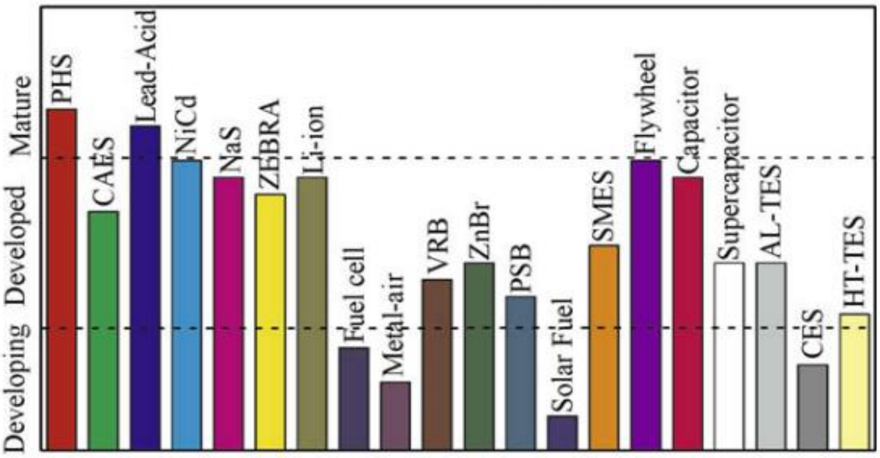

Figure 12 - Technical maturity for Energy Storage Devices (ESDs) [22]

- **Classification**

To compare critically between different storage technologies. Two criteria are used for that classification: function & form. Regarding its functionality, they are generally employed for power quality improvement or UPS purposes. On the other side, some other technologies are mainly designed for energy management, for instance: fuel cell, large-scale batteries. As shown in Figure 32; SMES, flywheels & supercapacitors fall into the category of power quality. Basically, this classification encompasses wide range of technical indicators that assess different ESDs. Thus, it is possible for manufacturers to develop some features of these storage elements in terms of energy for power quality purposes. Then, advanced batteries are commercially available for its various advantages such as: low cost, moderate size, long lifetime and fast charging.

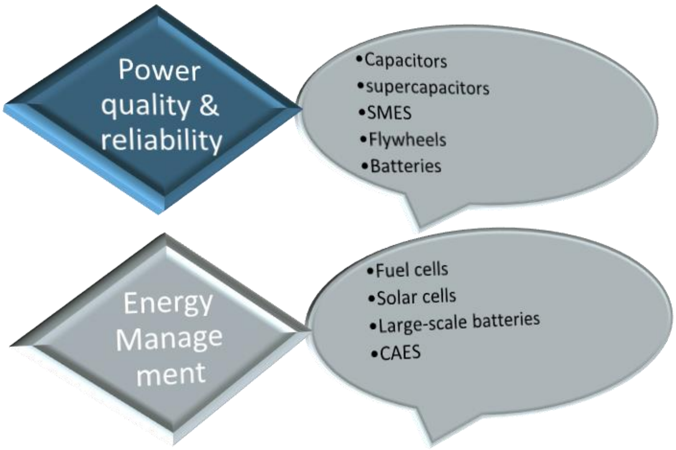

Figure 13- Energy Storage classification according to function

- **Area of applications**

  Nowadays, small-scale SMES becomes an important storage unit in microgrid. Due to its high efficiency & fast response, it contributes on power factor improvement and frequency stabilization. Moreover, it is a reliable back-up storage technology that can compensate energy in case of power interruption or mitigate the instability caused by momentary voltage dips. However, this technology is not suitable for long-term storage; unless it's designed in GW scale. Despite this, SMES overall cost is high because of the cooling requirements. Then, 2G HTS superconductor are frequently used for minimizing its cost. On the other hand, numerous ESDs, rather than SMES, have recently emerged in many applications. Batteries are suggested for long-term applications, where a continuous supply from few hours up to several days is required. Thus, they can be applied for power supply in distribution systems. Referring to Figure 12, Lead-acid technology is a mature technology which can be reliable for most of grid applications due to its low cost, effectiveness & high energy density. Sometimes, this technology is integrated in parallel with UPS devices to reduce any fluctuation in voltage or can supply specific loads, while UPS is off-line. From Table 1, battery's efficiency reaches up to 60-80%. So, the conversion from electrochemical to electrical energy is accompanied with some losses; which leads to a moderate efficiency. Furthermore, the internal resistance of EVs battery prevents its utilization since additional thermal losses would be dissipated during charging processes. Thus, this resistance reduction will tremendously affect the charging time for EVs. In fact, this advantage could encourage further utilization of battery's on EVs. Although the wider application of batteries, their high cost is limiting its consideration on such applications. For instance, lithium-ion battery stands for 1/3 of the Electric vehicle's total cost [30]. Compared with SMES, it exhibits low efficiency due to huge loss in power conversion. In addition, battery's discharge rate & lifespan are very limited. In large-scale industry, long lifetime cells are required to avoid high cost of that technology. On the other hand, supercapacitor properties allow its expansion in applications where the need to store or afford power in very short time (~ milliseconds) is necessary. However, its cost is much lower than SMES. Otherwise, both solutions are similar in their features. Supercapacitors could be used as an alternative to conventional batteries for electric vehicles. Further, it is considered as a back-up storage device for UPS.

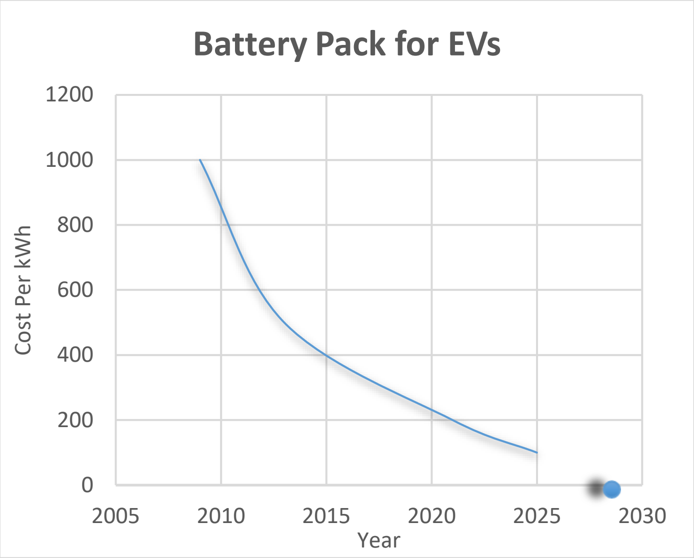

Figure 13- Battery Pack price for Nissan LEAF Vehicle over last decade [30]

Type	Efficiency (%)	Energy Density (Wh/Kg)	Power density (W/Kg)	Response time (ms)	Lifetime (year)	Cost ($/kWh)
Battery	60-80	20-200	25-1000	30	10	150-1300
SMES	95-98	30-100	1e4-1e5	5	30	High
Flywheels	95	5-50	1e3-5e3	5	20	380-2500
Supercapacitors	95	<50	4000	5	30	250-350

Table 1- comparison of several typical ESS [31]

Chapter 2 covers different areas of energy storage technologies. A brief review on short-term & long-term technologies, is made. A general interpretation about different technologies, ex: batteries, SMES & flywheels, etc.., were conducted. Furthermore, a review about specific indicators; that affects the efficiency for ESDs, were also pointed out with help of Ragone plot. Then, a complete assessment for these ESDs is made through clarifying which technologies can be applied on a specific application based on the research studies made for each of them. Thus, energy storage technologies are classified according to several functions. A critical comparison between those ESDs is included to differentiate between the most & least efficient technologies in different purposes. This can be a guide for different storage technologies in many applications' employment

Chapter 3. Superconducting Magnetic Energy Storage systems (SMES)

3.1 Background

Superconductivity - the absence of electrical resistance in certain metals at very low temperature - has been revealed after the analysis of electrical resistivity of mercury at 1911 By Kammerlingh Onnes. One of the most recent examples of superconducting technologies is Superconducting magnetic energy storage (SMES). This technology is mostly used in electric grid operations and developed for power system stability purposes. SMES proved an advantage over other storage devices due to its distinct characteristics of system efficiency's improvement. Moreover, High temperature superconductors (HTS), which operates in a temperature range between 20 and 70K, shows a distinguishable low cost compared with other conventional copper conductors. Other important feature of SMES is the cost scaling over size. Therefore, the cost per unit of stored energy (Mega Joule or kilowatt-hours) is inversely proportional to the storage capacity [25], [32]. Thus, it is a perfect storage solution coupled in systems, with large energy storage requirements and/or rapid power differences [27]. Other features that make SMES much more prioritized over other technologies is the discharge time (τ), up to milliseconds. In addition, SMES can compensate the diurnal energy demand in short time and provide surplus energy to storage units that has been designed for rapid intervention in case of severe actions or damages in the grid network [25]. Since, it is affirmed the significance of SMES in plenty of applications for modern power system. An outlook about superconductivity history and its first prototypes used in real-life practical events shall be a matter of interest before going into-depth for major technical & economical assessments for SMES applications. Particular attention would be assigned to different HTS materials and its contribution to several electrical power applications.

3.2 Superconductivity Theory

- **History**

Since its invention, the history of superconductivity is perhaps one of the most exciting adventures in physics. Superconductivity's discovery was attributed to the Dutch Scientist H. Kammerlingh Onnes in 1911 at University of Leiden, Netherlands. His journey begins when he successfully liquefied helium[5], reached up the temperature of 1 K, on July 10th 1908. This boiling temperature of Helium, itself, is not constant as it can be lowered by pumping. He focused on analysing the behaviour of electrical resistance

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[5] The boiling temperature of Helium is 4.2 K at atmospheric pressure

of some pure metals (Mercury, Lead and Tin) when lowering their temperature to absolute zero. Generally, the mechanism of electrical conduction, before the liquefaction of Helium, were not fully developed. Around room temperature, the electrical resistance usually exhibits a linear variation with temperature. Before the discovery of K. Onnes, there is unclear vision about the behaviour of resistance at very low temperatures but, in general, three cases were anticipated [33]:

A. *James Dewar* has shown that the electrical resistivity might approach zero value with decreasing temperature.
B. The resistivity of a metal reaches down a minimum value and rise again at still lower temperature "*Kelvin's Approach*".
C. The resistance ends up by having a finite limiting value when temperature becomes zero "*Matthiesen's Approach*".

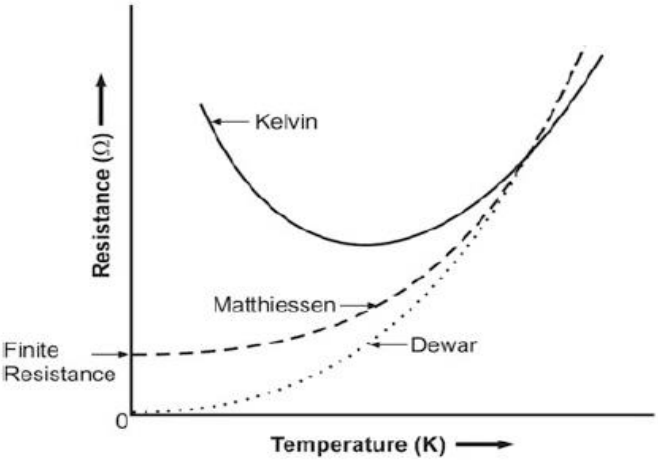

Figure 14 - three different predictions of Matthiesen, Kelvin and James Dewar regarding the temperature variation with the electrical resistance of materials. [33]

Before 1908, there were only presumption by most of great scientists that the resistivity of metals will decay to zero when the temperature approaches absolute zero or will drop to a minimum value then rise again and so on "Referred to Kelvin approach" [34]. Then, he had published his discovery in a note and has publicly recognized with a historical discovery of superconductivity; further explained by the disappearance of the electrical resistance of mercury below 4.2K in a sharp form, instead of gradual decrease with temperature, per shown in Figure 15 [35]. Onnes has commented himself this breakthrough by the following: "*At this point (Slightly below 4.2 K) within some hundredths of a degree came a sudden fall not foreseen by the vibrator theory of resistance, that had framed, bringing the* *resistance at once less than a millionth of its original value at the melting point*” [33]. Due to this discovery, H.K. Onnes received Nobel Prize[6] in Physics at 1913.

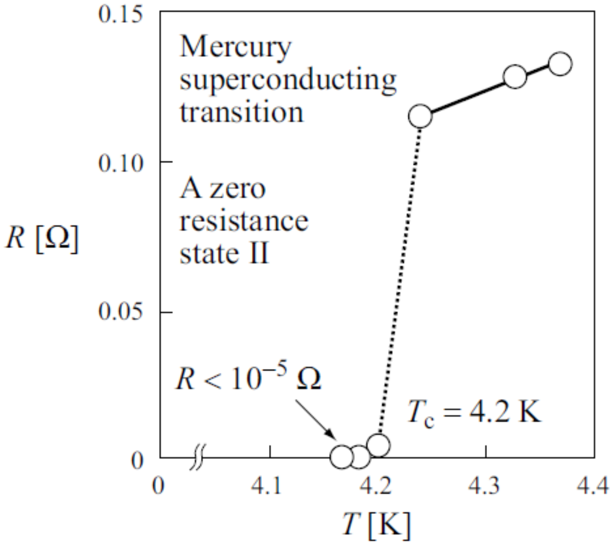

Figure 15 – The electrical resistance behaviour of mercury with a very low temperature (~ 4 K), the historical evidence of superconductivity noted by Heinke Kammerlingh Onnes in 1911 [35]

Within two years of superconductivity’s discovery, additional experiments are implemented to understand the behaviour of some materials (ex: mercury) when the temperature is altered. He has concluded that a reverse proportionality exists between the critical temperature of SC (T_c) and the current density (J_c). If this temperature is decreased below its threshold value, the current density of SC is increased per shown in the following equation:

$$J_c = J_c(0)\,\frac{Tc-T}{Tc} \tag{9}$$

This is applicable for most of LTS wires such as: tin, lead and Mercury. However, other factors have contributed on the quench of SC. It has been demonstrated that the applied magnetic field increases the heat dissipation on the line. Above a critical value, the SC ceases to operate. Then, it becomes a normal conductor [36]. An important discovery of Onnes was the stimulant for intensive studies to understand how the superconductor (SC) behaves under critical and harsh conditions. Therefore, the question posed at this time, **what is the behaviour of a SC under the subject of a magnetic field**? Thanks to the efforts done by Meissner and Ochsenfeld in that topic in 1933. They have proven that the magnetic field B is dislodged from SC. When a SC is subjected to an external magnetic field, the field lines are deviated from the SC. Thus, the magnetic field disappears inside the SC [35]. This study has shown that a SC is

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[6] The Nobel Prize award citation dated Dec. 10, 1913 states, “For his investigations on the properties of matter at low temperature which led, to the production of liquid helium” [34].

not only a perfect conductor (ρ=0) but also a perfect diamagnet (B=0). In contrary, it is shown later that the field penetrates a small distance inside the SC, called "London's penetration depth λ", which is estimated by 10-100 nm in the metal SC [34]. Successively, many theories and contributions have revealed the secrets of superconductivity theory. Bardeen, Cooper and Schrieffer have been awarded Nobel Prize in 1972 for their BCS theory that explain the "cooper pairs" in the SC; a pair of electrons that are bound together, due to a mutual small attraction, at low temperature in certain way. This theory has clarified a lot, in the macroscopic range of the SC material, about the superconductivity. Within the past 70 years, the conjecture between many researchers that superconductivity is only possible with low temperature liquid helium at T_c= 4.2K. In contrary, this has been changed in 1986, when Bednorz and Muller have initiated the HTS in copper oxides. This discovery has followed the discovery of Nb_3Ge[7] (Niobium-Germanium) after 13 years. However, the discovery of superconductivity in ceramic cuprates, by Bednorz and Muller, in 1986 above 77K (the boiling temperature of liquid nitrogen'LN_2') was an astonishing discovery and gives hope to discover further higher T_c's in metals [37]. The highest critical temperature T_c for HTS material reached up 135K that is attributed to, $HgBa_2Ca_2Cu_3O_8$, one of the copper oxide compounds under atmospheric pressure. The critical temperature for the latter compound become 164 K under higher pressure of 30 GPa [33]. Since then, eight different families of materials have been consequently discovered and joined the category of the high temperature superconductors (HTSCs) as it is illustrated in Figure 16. Many alloys have demonstrated similar behaviour as superconductors in liquid helium such as Nb_3Sn (Niobium Tin) and Nb-Ti (Niobium Titanium). These metals were called "Low temperature superconductors (LTS)". They can sustain their superconductivity state in higher critical fields, which make them attractive compared with other pure metals. Nb_3Sn and Nb-Ti are commercially available. Although their critical temperatures are 18 and 9 K. They must operate, in most of applications, below 5 K that necessitate the usage of cryogenic refrigerators. This cooling method seems expensive and unpractical for industrial application. Thus, the incentive to depend on HTS materials, due to their higher operating temperature, is much appreciated and applicable for a variety of electric power equipments. Prior to HTS utilization in several industrial applications, the development of methods to reduce the cost of HTS materials and increase their performance, while operating, is necessary and will be discussed further below at the next sections [32].

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[7] Nb_3Ge: Niobium Germanium is a Low temperature superconductor alloy discovered in 1973 having T_c=23.4 K. It is one of LTS superconductors and can sustain higher critical fields up to 10 Tesla.

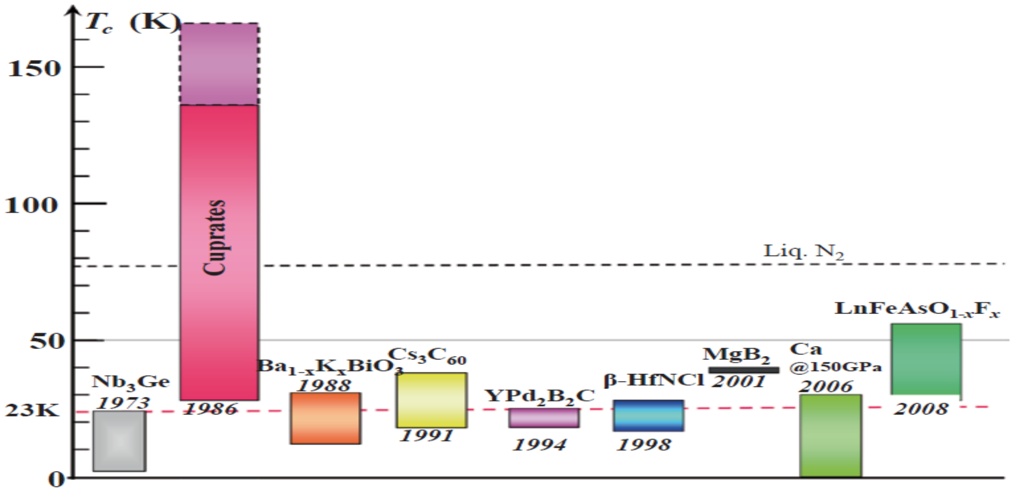


Figure 16 - T_c histogram, distribution of the critical temperature for eight families of superconductive metals and their year of discovery [37]

3.3 Types of Superconductors

A SC wire is named "practical" when it is available in specific lengths for building up devices. Such a practical SC wire is shaped as a composite structure to meet the required engineering characteristics by appropriate selection of materials. Basically, there are two types of superconductors: HTS & LTS. The latter must be cooled down below 4.2 K in a liquid helium. On the other hand, liquid nitrogen is necessarily used for HTS. The optimum operating temperature of HTS that are favoured for energy storage applications is around 50-70 K. It's crucial to point out that the boiling point for liquid nitrogen is 77 K. On the other hand, the most common HTS conductors in the industry are BSCCO-2213, BSCCO-2223, YBCO-123, REBCO and MgB_2. HTS materials are applicable in numerous applications. They are employed for building power cables & AC transformers in the electric grid. In addition, they are used for fault current limiter manufacturing. On the other hand, BSCCO-2223 conductors are proposed for Synchronous machines design due to their distinguished features of high current density. However, their expensive price is accounted as a challenge for a future consideration in these kinds of applications. Then, YBCO-123 coated conductors are supposed as an alternative solution due to its low-cost & larger current capability [32]. In contrast, the first used superconductors in the industry belong to LTS family such as Nb_3Sn and Nb-Ti. LTS was likely used in several purposes because their sustainability for higher critical fields. Moreover, Nb-Ti alloy seems to be more effective for SMES. For instance, its current-carrying capability is relatively high and reaches up to 2 kA/mm^2 when subjected to a very low temperature 4.4 K at a field of 5 T. Generally, the quality of SC is measured by its current density limit during zero resistance. Furthermore, the operational current density for Nb-Ti is approximately 100 times compared to the copper operational current density. For low temperature SCs, this parameter exhibits impressive values up to kAs while it is lower for HTS wires because of their higher critical temperature. The only defect associated with LTS family is the expensive price for cryogenic generators. As shown in Figure 17, various cross sections of Nb_3Sn wires produced by various manufacturers were presented. Although, it's difficult to apply 1G-tape BSCCO under high magnetic fields since its critical current declines rapidly. Then, it's rarely used for power applications that require high field [38].

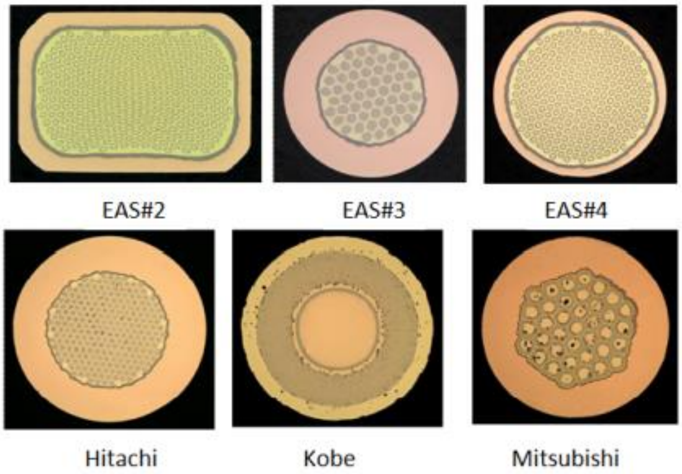
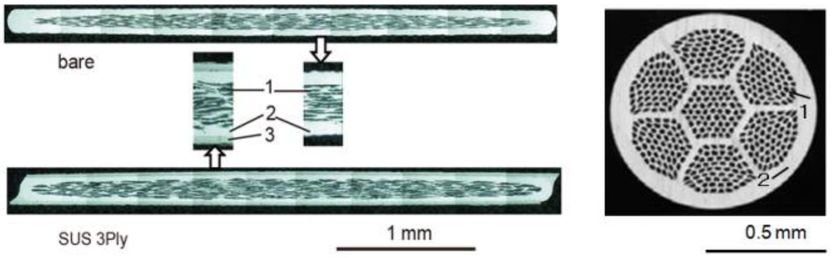


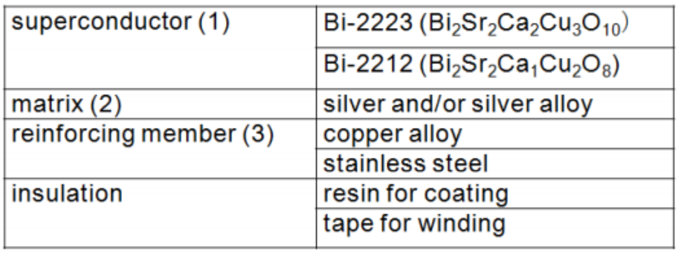
Figure 17 - cross-sectional view of Nb_3Sn wires produced by several manufacturers

HTS are divided into two main categories: 1G, 2G superconductors. In most cases, 2G HTS tapes are used for many power applications. With respect to 1G HTS wires, two practical SCs are commercially employed: BSCCO-2212 & BSCCO-2223. Their cross section is round or flat based on the fabrication techniques. Other SC wires might have supplementary stabilization or reinforcement materials to improve their characteristics. Further elements and materials, in Table 2, are additionally integrated in superconductors inner layers for meeting the required characteristics of solidity per recommended in technical report IEC 61788-20 [39]. SC wire has enough electrical and mechanical integrity for proper operation in the selected application. Conversely, YBCO-123, ROEBEL cables are examples of 2G conductors that are widely used in large projects. In their manufacturing, additional stabilizer layer might be included for protection reasons in high voltage applications. This stabilizer is made from copper. Otherwise, they could be stabilizer-free tapes per shown in Figure 4 [40].



(a) BSCCO-2223 (b) BSCCO-2212

Figure 18 - cross sectional views for practical 1G HTS BSCCO-2223 & BSCCO-2212



superconductor (1)	Bi-2223 ($Bi_2Sr_2Ca_2Cu_3O_{10}$)
	Bi-2212 ($Bi_2Sr_2Ca_1Cu_2O_8$)
matrix (2)	silver and/or silver alloy
reinforcing member (3)	copper alloy
	stainless steel
insulation	resin for coating
	tape for winding

Table 2- different materials & composites used for practical 1G HTS wires fabrication

3.3.1 BSCCO-2223

BSCCO-2223 is the only material which is commercially available & produced for high-field magnets, fault current limiters & power cables manufacturing. After its discovery, its low critical current prevents their implementation in large-scale projects. Among various manufacturers of BSCCO wire, American Superconductor (AMSC), USA & Sumitomo Electric Company (SEC), Japan are the prime players supplying these materials for industrial applications. AMSC has deployed an effort for increasing its critical current up to 100 A. Basically, AMSC supplied two types of wires (filaments). 1G-HSP HTS (high strength plus HTS wire) is dedicated for applications where high mechanical strength is a requirement. Its thickness is approximately 0.26 mm & total width is ~ 4.2 mm. In addition, J_c for BSCCO wires rated 13.3 * 10^3 A.cm^{-2} [34]. Even, it has a maximum tensile strength of 250 MPa at 77 K. This strength is defined as the maximum load sustained by a material before breakdown. If the strength > 250 MPa, the multi-filamentary wires of BSCCO-2223 loses its properties & the wire ceases to be used as a superconductor. These wires are encased in Ag-alloy matrix with Stainless-Steel (SS) lamination. This lamination provides more stability for electrical, thermal and mechanical properties of such magnet through minimizing the electrical contact between HTS pancake coils [41]. Further, Sumitomo had introduced several modifications in Bi2223 material structure to enhance the physical properties of the SC [42]. They have developed BSCCO wires in a longer lengths of 2 km. Then, its critical current value is increased up to 200 A. Even though, it can be produced in a few metres with a maximum critical current of 250 A.

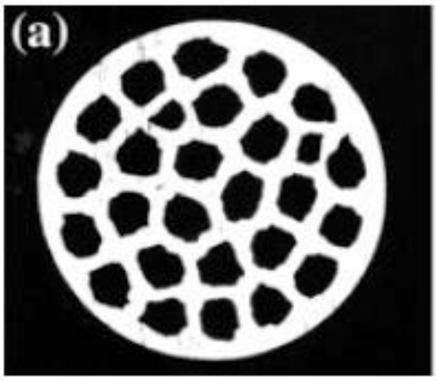


Figure 19- A cross section of multifilamentary BSCCO-2223 Wires [34]

In addition, sintering process has been carried out to increase the critical current up to 218 A for 1 mm^2. For high pressure requirements, SS lamination is implemented for giving the conductor/wire more rigidity. For instance, 400 MPa can be applied on such wires without losing their properties. However, its critical current density (J_c) drops sharply in increased magnetic field when operated at high temperature, 77 K. So, this fact reduces the reliability of high T_c materials employment.

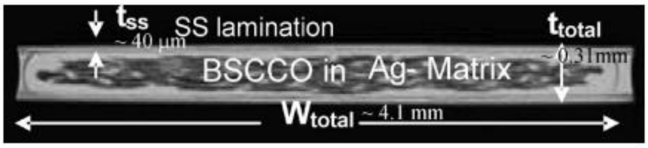


Figure 20- A micrograph of SS-laminated BSCCO tape [41]

3.3.2 BSCCO-2212

Bi 2212 wires filamentary structure allows the manufacturing of Rutherford cables due to its demonstration of high field production & large current densities. However, it's rarely employed in commercial applications because of its lower critical temperature (T_c). Most of these electro-technical devices, at this time, were reliable on HTS technology. Then, this type of filament is not suitable on these applications. It's also used for Powder-in-Tube (PIT) wire filaments production since it carries large currents while producing high field > 20 T at very low temperatures. A cross section of high current tapes is demonstrated in Figure 21. One of the shortcomings of Bi 2212 wires is the existence of a soft Ag alloy matrix which limits the longitudinal stress in range of 100 and 180 MPa. As a consequence, this will have an adverse impact on the critical current leading to a quench of its superconductivity [43].

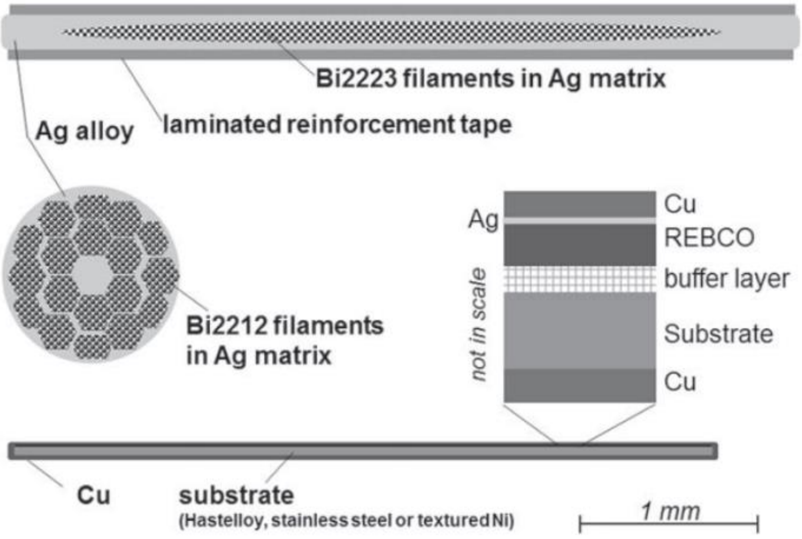


Figure 21 - Schematic cross section of a Bi2212 wire [43]

3.3.3 MgB_2

As explained before, most of superconductors are categorized into two types: LTS or HTS. Since the critical temperature for MgB_2 is around 20 K, we could treat it as an intermediate type of superconductor (MTS). Often, they are used in different power applications because of its cheaper cost. However, some limitations have prevented its wider consideration. These can be obvious when discussing the V-I characteristics of superconductor. Basically, an approximate linear V-I is accounted for a normal superconductor. For superconducting wires, an important indicator is denoted as “N value”. This parameter defines the relation between the applied current to the tape or wire and the voltage drop across its terminals. Above the critical current, the superconductor quenches and a linear relation is anticipated. Before I_c, the relation takes an exponential shape. For MgB_2, N-value is low which restricts its efficacy in wider applications. In addition, research has shown that a chemical reaction is built when mixed with copper. This reaction has a reflection on the quenching stability of a SC which affects its functionality & requires the definition of SC critical state. Another limitation appears in the difference between the required operating current & critical current. The critical current (I_c) is defined as the current; corresponding to a voltage drop across the wire or tape (E= 1μV/cm). Ultimately, the operating current is below that limit and shouldn’t exceed I_c.

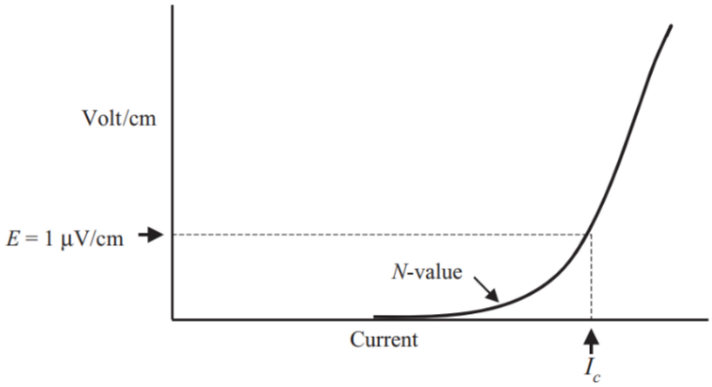


Figure 22- V-I curve for MgB_2 superconductor

3.3.4 YBCO-ROEBEL CABLES

Recent progress on the development of 2G HTS are suggested for increasing the current density capability of YBCO filaments. Additional requirements of AC loss reduction are also considered. YBCO filaments might be used for constructing strands of wound cables in automated machines. Two YBCO filaments are mainly applied to form YBCO strands (12mm wide, 40mm wide). For high DC current applications, a 5 mm wide 10 or 15 strands cable has been selected for delivering 700-2000 A at 77 K. While a 2 mm wide 5 or 10 strands have been chosen for conducting the same transport current but one half of AC loss for a regular 4 mm single wide tape [44]. Conversely, the cost of 12 mm-width for YBCO tape is 85 $/m according to Superpower Inc [45]. ROEBEL cables are wound by windings transposition. This latter gives more insight about its consideration in different applications since it conducts high current & reduces the coupling loss inside the SC. In research, they are modelled in 2-D & 3-D approximation due to its structure complexity. Based on latest experiments, certain reduction is observed, in crossed-strands parts of the cable, if the transposition length is assumed higher than the cable width. Generally, cables are identified by number of strands / width of strands in mm. Then, 15/5 cable has 15 strands each 5 mm width [46]. A typical design for HTS cable is necessary before implementation in offshore or solar plants, for instance. The following table illustrates a DC HTS Cable characteristics that are required for several applications. It's noted that the immersed liquid is LN_2 & the critical temperature is 77 K. The critical current, which is 330 A, is the maximum current that could be maintained by the cable without losing its superconductivity. If this current is exceeded, the cable quenches & transforms to a normal conductor.

Manufacturer	Superpower
Type	flat tape
Nominal Width	12 mm
Nominal thickness	0.1 mm
YBCO thickness	1 μm
Stabilizer (Copper)	2x20 μm
Substrate (Hastelloy)	50 μm
Critical tensile strength	550 MPa
Critical current, 77 K – self field	330 A

Table 3- Main characteristics of HTS YBCO conductors

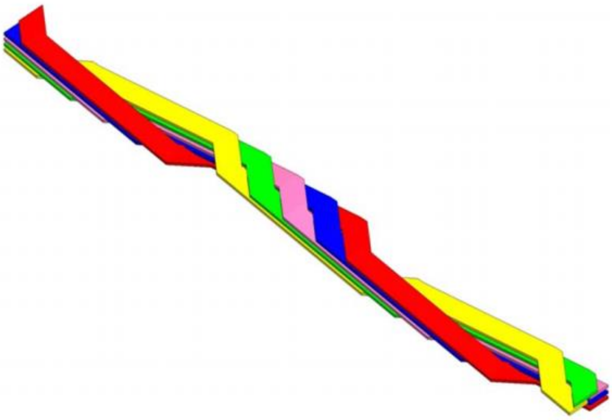


Figure 23- Typical structure of a ROEBEL cable [46]

3.4 SMES components

A typical SMES system consists of four main parts, the superconducting coil with the magnet (SCM), power conditioning system (PCS), coolant system and the control unit (CU). SC, CG are both deployed to store electrical energy. The driving circuit is installed to control the power transfer to/from SMES. As depicted in Figure 24, SMES system consists of AC voltage source, transformer, converters and magnet coil. PCS is responsible for AC/DC conversion. Then, SC will be feed up with DC current. Moreover, the load voltage is stepped down through DC chopper to rated values. In addition, the circuit is secured against any unforeseen event, for instance: inverter damage, by using a Bypass Switch; used to reduce energy losses when the coil is on standby or if the inverter switch is not functioning well to prevent the current interruption from SMES coil [47]. In such cases, the power does not pass through the inverter. Thus, it is well important to provide an alternative path for power flow to the SC coil. If the utility tie is lost, that switch maintains a continuous power flow to SMES. In contrast, the coil has some protection for any expected failure or breakdown.

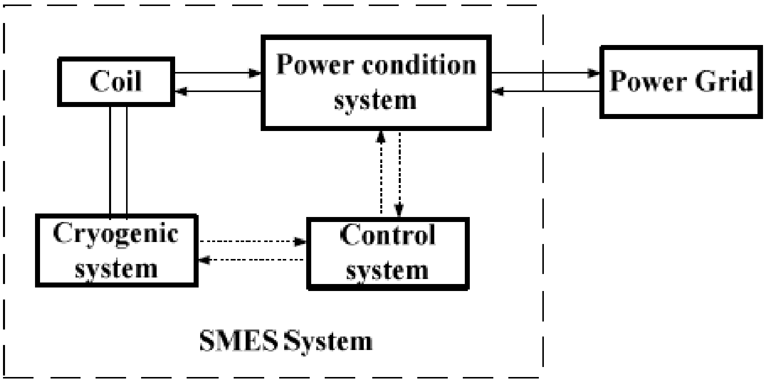


Figure 24- SMES system connected to power system [45]

If SC is damaged, the controller sends a signal to the protective element for activation. The coil design must be accurate & well-protected to prevent any additional cost. Other topologies should have the same objective; storing the energy in a SC coil, but the elements are scattered in different ways and the protection system is somehow variant. For successful design, the circuit must be functioning and well controlled by means of a CU. The CU consists of microcontroller or DSP. Its role concerns the detection of any faults in the electrical loop, it sends signals in form of digital codes 0 or 1 for activating or de-activating such elements until the fault is cleared.

1. Superconducting coil & Magnet (SCM)

The SCM comprises of the superconducting coil, magnet and coil protection. Generally, any inductor has an ohmic resistance. So, the distinguished feature of energy storage inside the coil is not anticipated. To remove the ohmic resistance from the coil, the inductor coil must be cooled down to lower temperature; at which the resistance is minimum. When the coil temperature decreases to reach a minimal point close to zero kelvin, the conductor becomes superconductor. In this case, the current carrying capability would be large enough and the resistance vanishes [48]. Generally, the magnet design necessitates some pre-assumed data, like the amount of energy stored in coil, operating current, operating temperature, cooling methods and maximum available length of superconducting tape required for the design. So, appropriate selection of HTS tape is very important for SMES design since it has high magnetic field. Briefly, YBCO conductors were considered for higher field applications due to its attractive critical current characteristics at high magnetic field. In opposition, LTS materials are applicable rather than HTS because the current density would be higher while temperature becomes as low as possible ~ 4.4 K. In contrast, the current carrying capability of a conductor is inversely proportional with temperature. If the temperature rises, the current density becomes low. Otherwise, the temperature drops under some critical points would result in a very high current density, which is a great advantage for a SC. However, it is necessary to protect the SC coil against failure, which may cause serious damage to SMES systems [24]. The strength of magnetic field and efficiency of SC is determined by its quantity factor, as illustrated in eq. (10) [48].

$$Q_{sc} = 5 * 10^3 \left(\frac{Em^2}{Bm}\right)^{1/3} * \left(\frac{1}{\sqrt[3]{\left(\frac{r}{a}-1\right)\left[\frac{r}{a}-\left(\frac{r^2}{a^2}-1\right)^{\frac{1}{2}}\right]^2}}\right) \tag{10}$$

It should be noted that r, α and B_m parameters are constant. So, the quantity of superconductor is directly proportional with the maximum energy stored in the coil "$E_m^{2/3}$" for any geometries of SC. Hence, the unit cost for the superconductor in $/MJ, employed in large magnets, will be less compared to small magnets.

2. Ferromagnetic core

Ferromagnetic core inside the SC coil enhances the storing capacity of SMES. At low energy density, storage of huge amount of energy is quite possible. For high gain, there are multiple configurations used to minimize the flux leakage inside the core such as "**The closed core**", "**the pot core**". *The closed core* is designed in an arrangement; that occupies the volume both inside and outside the coil, for the sake of minimum flux leakage inside the core. *In the pot core*, the flux leakage is negligible as the cross-sectional area along the flux path remains constant. The maximum energy stored in the coil, surrounded by a saturated pot core could be estimated by the following equation. Accordingly, both inductance of the core and coil contributes, effectively, on the growth of stored energy capacity in inductor [49]. The maximum stored energy is determined according to coil's size & geometry.

$$E_m = \frac{1}{2} LI^2 \sim \frac{1}{2} B_s INS \tag{11}$$

- L: coil inductance with the core,
- I : SMES current
- B_s: saturation magnetic induction in the core

❖ **Solenoid coil:**

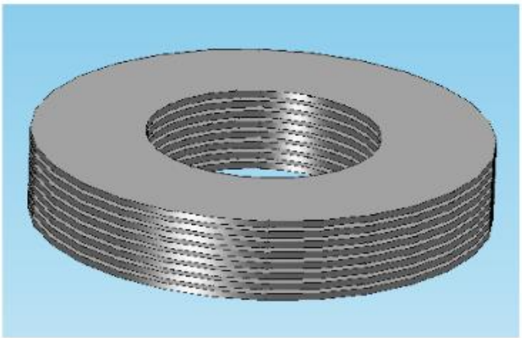


Figure 25- Solenoid Magnet Arrangement (Closed core) [38]

- Solenoid arrangement is preferably used in medium scale
- Has as a low mechanical stress & high stray magnetic field
- Apply long length of wire
- Arranged in series or parallel per energy requirement
- Used superconductors: MgB_2, 1G HTS tape

❖ **Toroid coil:**

- This arrangement is required for large SMES
- Has a low stray magnetic field,
- Apply shorter length of wire & require smaller space
- Cost-effective; for high magnetic flux density, coil made out of 2G HTS is more economical.

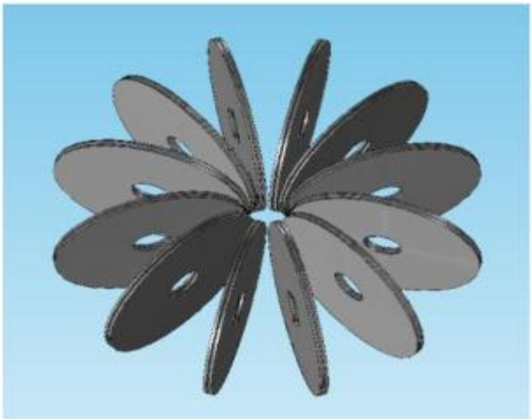


Figure 26- Toroid Magnet Arrangement (Pot core) [38]

- **Different Scales of SMES systems**

In addition to the above specifications, bigger radius was selected for reducing the magnetic field & improving the storage capacity. However, additional lengths of SCs are required when radius increases. As shown in Table 4, the unit cost per stored energy decreases when the stored energy increases from kJ to GJ. Thus, it's suggested to install large-size SMES, although its incremental price. Conversely, the total cost for superconductor tapes "Solenoid and toroid" rated in kJ, MJ and GJ are $14000, $1.02 M, $ 425 M and $450 M respectively. As will be discussed later in Chapter 5, the capital cost is the basic cost of SMES system including: magnet structure, cryogenic generators, power electronics components, etc. Two different parameters are considered, in that term. Energy capacity-related cost & power conversion cost. From these terminologies, we might understand that power conversion cost consists of the essential components relevant to intermediate device "Choppers, switches". Ultimately, this parameter varies according to the application based on the used power electronic equipment.

Parameter	1.2 kJ (solenoid)	1.6 MJ (solenoid)	1.3 MJ (toroid)	1 GJ (toroid)
Radius	6.8	28	12	86
Total length of tape (km)	0.17	12	5	533
Cost (USD)	$1.4*10^4$	$1.02*10^6$	$4.25*10^5$	$4.5*10^7$
Unit Price ($/J)	1.4	0.64	0.33	0.045

Table 4- Cost of different scales for SMES system [45]

3. Refrigeration

Refrigeration is responsible on preventing excessive heat dissipation by cooling the relevant equipment in a specific temperature. Generally, storing energy in a purely inductive load is not applicable, due to its internal resistance. This resistance can be diminished by reducing the temperature of the coil itself. Then, a coolant is used in SMES system. HTS is cooled at 77 K using liquid Nitrogen (LN_2) and LTS is cooled using liquid Helium at 4.2K. LN_2 is used due to its cheaper cost, higher operating temperature with maximum cooling efficiency. This efficiency is directly relevant with the cooling temperature. If the coil is cooled under 77 K, the cryocooler can provide 20 kW. Otherwise, the cooled power is 4 kW for 20 K [50].

$$\eta_c = \frac{T_l}{T_h - T_l} \quad , \qquad (12)\ [32]$$

- **η_c**: Carnot efficiency
- **T_l**: Operating temperature
- **T_h**: Room temperature

For an ambient temperature (T_l ~ 77 K) & room temperature (T_h ~ 300 K), the efficiency is almost 34.5%. As a general rule, refrigerator's efficiency is approximately 20% of the carnot efficiency. Then, η is equal to 6.9%. To obtain the specific power, its value is dependent on the efficiency, as shown below:

$$P = \frac{1}{\eta} \qquad (13)$$

- P: Specific power (kW)

According to cryocooler's efficiency, the specific power is almost 14.5. Normally, this parameter is measured in Watts & reflects the ability of cryostat to remove one unit of heat and the input power required to implement that. The above result signifies that 14.5 Watt is required as input for removing one watt of heat in 77 K cooling temperature. To distinguish between cryostats, this value should be low to reduce the required input power to its minimum values. For LTS conductors, additional power is required since carnot efficiency is decreased. This fact pinpoints that HTS are more preferable, in usage, than LTS due to its cheaper cost since additional power necessitates more expenses in terms of increased capacity.

- **Cryostat Assembly**

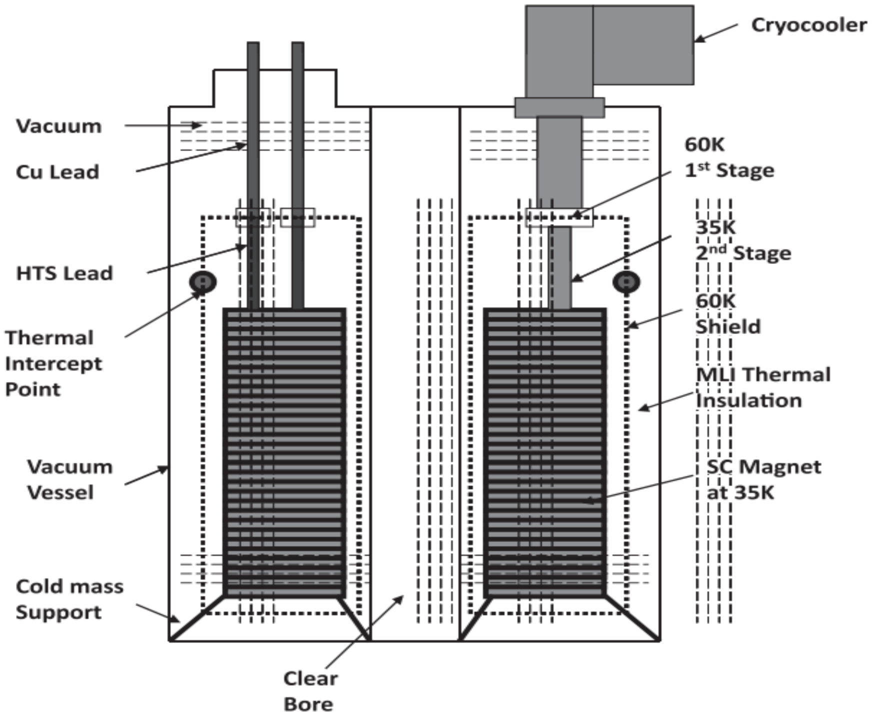


Figure 27- Schematic for a cryogenic generator used for a typical magnet [32]

A cryostat is responsible for cooling superconducting magnet coil & maintaining its temperature below the critical value. This will keep the SC in a good condition during its operation without losing its superconductivity. For HTS wires, the cooled temperature varies according to the system requirement. For a specific magnet, the allowed temperature is kept around 30 K. In context, the cryostat system consists of: Vacuum Vessel, HTS magnet, current leads, multi-layer insulation (MLI), cold mass support and cryocooler. A two-stage cryocooler has also been used for cooling a magnet in 4 K temperature. In that illustration, HTS magnet coil is cooled through the installation of a single-stage cryocooler under T= 30 K.

3.5 Superconducting Magnet design

To fulfil a complete design for SC magnet, a pre-selection of the conductor type is a first task to do based on the discussed criterions for each of superconductors. Then, BSCCO-2223 is a good candidate for employment in high-field magnets. In fact, high magnetic field is ultimately used at different applications in industrial production, electrical power & MRI. For high-field applications, special magnet requirements have to be met to operate steadily without any significant challenges. First of all, Ampere turns is a prime indicator for an optimal coil design. This parameter reflects the required coil's current for magnetic field generation on the magnet axis. Then, the coil size is another requirement, for further consideration, to design a coil. A detailed SC design is clarified in Table 5.

Magnet coil design (BSCCO-2223)	
Parameter	**Value**
BSCCO-2223 dimensions	
▪ **Width (mm)**	**4.4**
▪ **Thickness (mm)**	**0.29**
Required Ampere turns (kA)	**385**
Number of pancake coils	**30**
Turns/pancake coil	**70**
Operating temperature (K)	**35**
Total wire for the coil (m)	**1350**

Inductance of the magnet coil (H)	**0.83**

Table 5- magnet coil design details for BSCCO-2223 superconductor wire [32]

- **Flexible Alternative Current Transmission System (FACTS)**

Basically, FACTS is employed in modern power systems for increasing the capability, controllability, and the stabilization of main transmission line parameters: frequency, voltage, current. Then, SMES-STATCOM interconnection exhibits higher reliability & performance for FACTS apparatus. Because of this interconnection, SMES allows STATCOM to inject and/or absorb active & reactive power simultaneously instead of unidirectional power controllability. Voltage instability has also been smoothed-out by incorporating SMES with the grid. SMES is very effective to stabilize the dynamic system voltage by modulating the active & reactive power into the line, in a very short period ~ 5ms. Multiple generators connection, with the grid, is possible only; unless SMES is considered, because of its capability to stabilize the system voltage. As shown in Figure 28, SMES-STATCOM controller is located at Bus A, near the generation side. Based on numerical analysis suggested by Arsoy and his co-authors [51]. The controller location, according to generator's location, affects tremendously the system oscillations damping results. They have proposed a control strategy for a SMES-STATCOM apparatus and the location of the controller closer to the generation side shows better results related to the dynamic system performance with respect to this apparatus relocation far from the generator. The stabilization rate for the system oscillation is also higher at Bus A rather than other buses. Various applications are accounted, as well, in power systems and by means of SMES, unwanted behaviour; in terms of "**transient voltage**, **current fluctuation/ harmonics**, **frequency oscillations**, etc." might be eliminated.

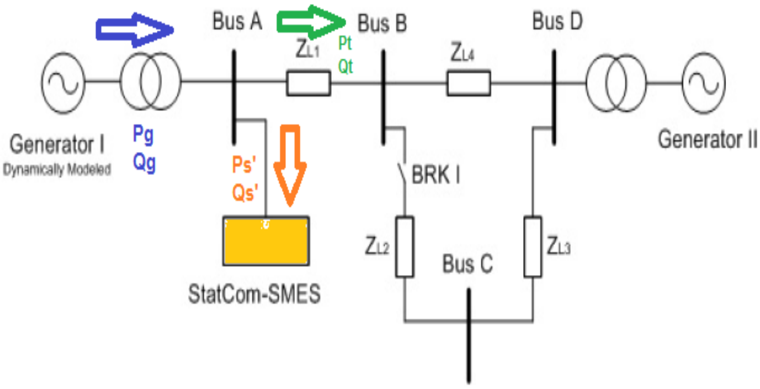


Figure 28- Configuration of FACTS enhancement in a multiple AC generation system

In this chapter, the history of superconductivity has been highlighted and how this phenomenon is developed over the last century since the discovery of HTS types of superconductors. Lastly, several power applications have recommended the integration of the superconductivity with its principle operation due to their distinguished features. Regarding SMES, several configurations of coil arrangements are illustrated while comparing between them in terms of cost, usage, etc. In addition, a critical comparison; between different superconductor materials, is made to determine the appropriate conductor based on the required characteristics of system. For other SMES components such as: refrigeration system, coil design, a brief explanation about each of them is shown as it would be used as a reference for SMES system configuration.

Chapter 4. Power Conditioning System and SMES control system

4.1 Overview

An unprecedent development of semiconductor technology, especially in switching speeds & power handling capabilities, has resulted in the advancement of power electronics field [52]. Generally, SMES can store energy in superconducting magnets through DC-DC chopper. Then, we might find multiple topologies for SMES. Often, Voltage Source Converters (VSC) are mostly used for SMES applications which relies on a stable line voltage. There are two modes for this topology: Charging, Discharging modes. When the coil stores energy, the power conversion system (PCS) initiates a positive voltage across the coil terminals. Alternatively, the coil discharges its stored power while the voltage is reversed to negative [53]. The polarity reversibility for voltage is a distinguished discrepancy between these two modes. On the other hand, Current Source Converters (CSC) is different from VSC that it converts AC current to a constant DC current stored in the magnetic field produced by the SC magnet. This is a necessary condition for power storage in SCs. It's mainly used for reactive power compensation. A strong grid with sufficient short circuit power is a necessary requirement for CSC to avoid commutation faults [54]. Compared to VSC, CSC allows high storage capacity with minimum losses but requires large stations for operating with maximum efficiency. In contrast, CSC permits higher switching losses which is not the case in VSC. Then, CSC is not the optimal topology for SMES modelling. Thus, VSC is a suitable Power Conditioning System (PCS) which can provide smooth inputs to SMES. A detailed description of its distinguished characteristics will be shown in the following sections.

4.2 Voltage Source Converter

A PCS is a necessary element to interface between the AC grid and the superconducting coil. This intermediate equipment controls the active & reactive power flow between these systems. In fact, VSC is much suitable for SMES despite its similarity with CSC. It's recommended especially, in FACTS capacitor. In addition, a Wye-Delta transformer (66/2) KV is connected at the AC input side for stepping-down the voltage to an acceptable applications, according to [55]. The basic topology for SMES, as shown in Figure 29, consists of two main parts: Voltage Source Converter (VSC) and two quadrant DC chopper, which are linked by a DC limit. VSC is composed of 6 pulse bridge, each bridge leg is made up of a reversed diode in parallel with IGBT to block voltage in one direction and conduct current in both directions to allow the flow of reactive power.

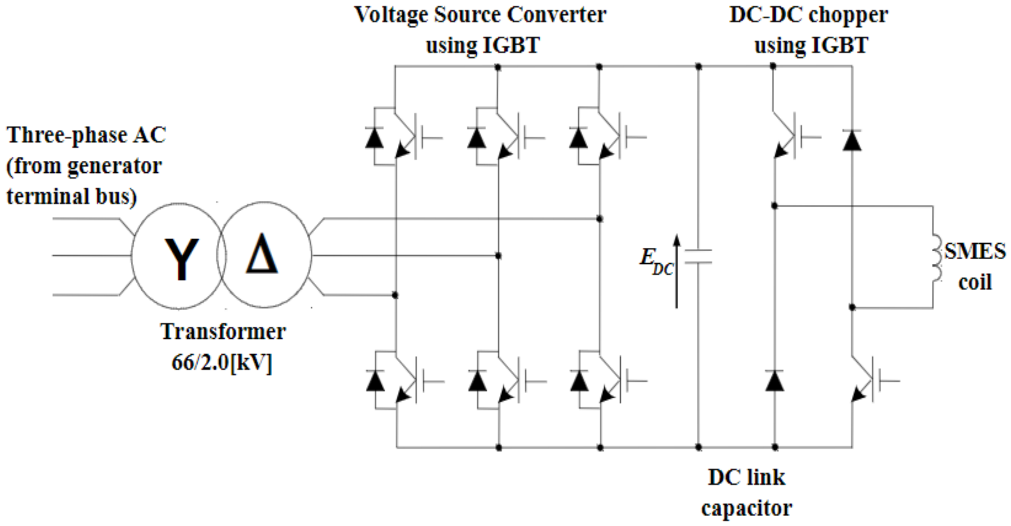


Figure 29 - A Basic topology of VSC-Based SMES system using 6 pulses IGBT

Through a proper control of trigger signals of IGBT, VSC is able to control the AC side line currents. In effect, the reference signal[8] is compared with a triangular carrier signals. Then, the result is a Pulse Width Modulation (PWM) signal that controls the switching process for VSC. On the other side, two-quadrant DC/DC chopper is effectively controlling the charging & discharging process of SMES to fulfil the required power transfer. If IGBT switches are turned-on, the voltage across SMES coil is positive. Then, SMES stores power. Further, DC capacitor affords a stable voltage & reduces the ripples of the DC output. Otherwise, SMES transfers its internal power, through diodes, to the main grid. Accordingly, the active & reactive power conversion between the main grid & SMES is successfully modulated. VSC is often used for highly inductive loads. Semi-controlled converter employs the mix of both diodes and thyristors. Unlike the fully controlled unit, the applied converter will provide a unidirectional flow of current and will not permit a bi-directional flow.

Per illustrated in Figure 30, Three level module VSC is applied in series with SMES through DC-DC converter. Since SMES will act as an energy storage unit. Although VSC-SMES has a double units of energy storage, the main role of the converter is maintaining a stable output DC voltage & reactive power compensation. Other objectives might be accounted as a back-up protection, if any mismatch happens in the main circuit [56]. A capacitive limit (V_{dc}), worth 150000 μF, is connected to maintain output stability for the choppers input. If any rise occurs across these terminals, the capacitance can regulate that while preventing any further damage that can result from this disturbance. It's always used for flicker alleviation.

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[8] The reference signal is the AC input signal which is given as three-phase sinusoidal wave.

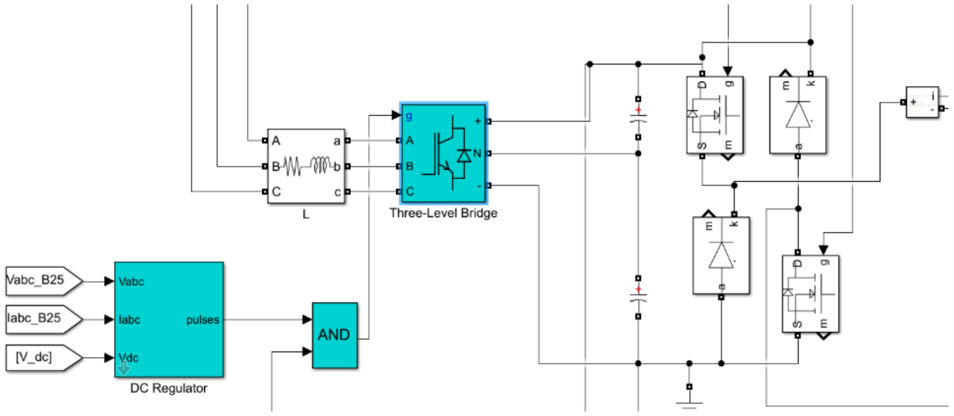

Figure 30- Three phase VSC model connection with SMES (Simulink)

4.3 Current Source Converter

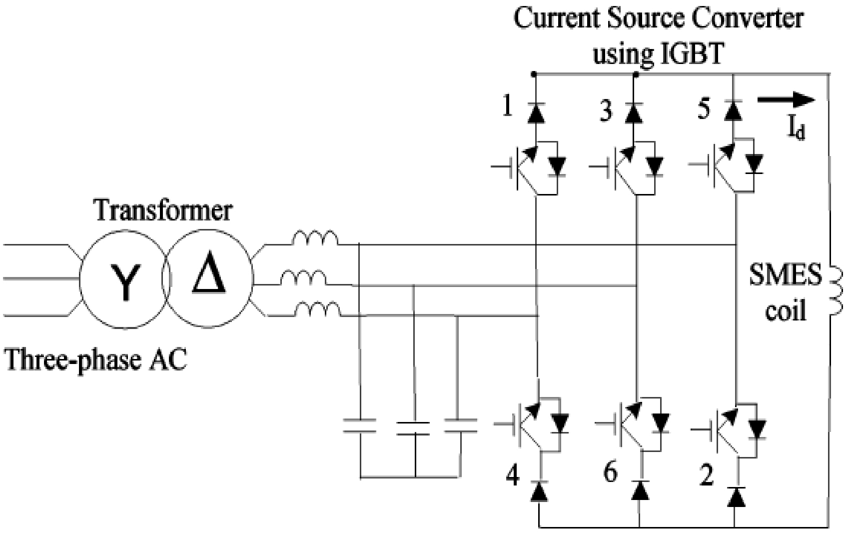

Figure 31 - SMES system with a CSC

Compared to VSC, a better performance is anticipated by using CSC based on recent study [55]. As discussed in Section 4.1, current-source converters are considered for industrial applications since it allows high storage capability. Then, a brief description of CSC-based SMES is essential before exploring the pros & cons for these two topologies. Per shown in Figure 31, a Wye-delta transformer is installed for modulating the voltage to permissible limit for CSC. Thus, three capacitor banks are used for reactive power compensation & provides voltage support across SMES coil. In addition, they're used to buffer[9] the energy stored in line inductances in the process of commutating direction of ac line current. Moreover,

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[9] This technique is mainly used for providing high storage capacity for the coil/inductance without affecting its life time & smoothing out the output ripples.

capacitors can filter high-order harmonics of the AC line current. By successful regulation of the switching devices trigger signals, the current in the SC coil can be re-adjusted to generate controllable three-phase PWM current at the AC side. CSC can provide high reactive supply for power compensation with minimum ripples. These distinct features of CSC has contributed in the mitigation of SMES AC losses & has extended its utilization for high-power applications. Thus, N semiconductor devices could be easily connected in parallel; forming multiple bridges. Another topology of 12 pulses CSC-based SMES has also been suggested for total reduction of AC losses & minimizing the ripples on the DC-side [47]. Another advantage of this topology concerns the reduction of Total Harmonics Distortion (THD) for 5th, 7th, 11th & 13th harmonics through the adjustment of modulation index M, as shown in the Figure below. Consequently, this will have an impact on PWM switching method for AC/DC converter [57]. Typically, M varies between 0.2 and 1. Thus, DC voltage across SMES is directly proportional to this index, that reflects the charging rate of the inductance. In Figure 32, a closed-loop feedback control method is applied to control the DC current for CSC-based SMES. The DC output current is compared with a reference value (I_{dref}) which results in an error signal (e). To get a better accuracy, e should be very close to zero. R_d is defined as the circuit resistance. For SMES circuit, the internal resistance of the coil is often minimum while L_s denotes to the coil inductance.

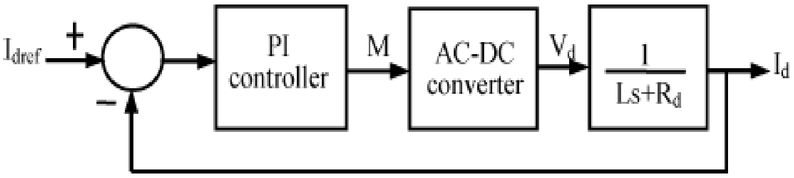

Figure 32- Block diagram of the DC current control algorithm

4.4 Thyristor converters

SMES could have hundreds of designs & configurations; by which they have tackled a specific barrier or obstacle in the power system. They are fit with multiple grid problematics and can mitigate most of them through selection of proper driving circuit for getting the optimum dynamic performance. Thyristor-based SMES is a different topology, employing thyristors instead of IGBT switches, that consists of a Wye-Delta transformer, AC/DC thyristor-controlled bridge converter & superconducting coil or inductor. The charging & discharging process is mainly controlled by adjustment of the firing angle (α). According to α, the converter initiates positive or negative voltage across SMES coil. If the firing angle is less than 90º, the converter operates in the rectifier mode (charging) & the voltage is positive. However, the converter works as an inverter when α > 90º. Then, the voltage across SMES is reversed to negative. As a result, the power can be extracted or injected from the power grid according to the objective [47]. The converter design is crucial when talking about the PCS as the latter will control the switching events and based on these events, SMES unit will act as a storage device or a back-up supply for a specific load. Then, the voltage computation on the DC side of the converter should be considered and is expressed by the following equation:

$$V_{sm}=V_{sm0}\ \mathrm{COS}\ (\alpha), \tag{14}$$

Where,

V_{sm0}: the ideal no-load maximum DC voltage of the bridge

In fact, the superconducting inductor current and voltage are dependent and the current is expressed as a function of the inductor's voltage.

$$I_{sm}=\frac{1}{Lsm}\int_{t0}^{t} Vsmdt + I_{sm0}, \tag{15}$$

I_{sm0}: the initial inductor's current.

Therefore, the real power P_{sm} absorbed or delivered by the SMES might be computed by:

$$P_{sm} = V_{sm} I_{sm}, \tag{16}$$

Generally, the inductor current is irreversible. Then, the converter output power P_{sm} is uniquely a function of α. Consequently, the energy stored in the superconducting inductor is:

$$W_{sm} = W_{sm0}+\int_{t0}^{t} Psmdt, \tag{17}$$

$W_{sm0} = \frac{1}{2} L_{sm}\ I_{sm0}^{2}$ is the initial energy in the inductor

From equation (16) & (17), thyristor-based SMES is mainly applied if the active power control only is concerned. However, its capability to control both active & reactive power, instantaneously, is low. In contrast, several configurations are introduced for both active & reactive power flow control.

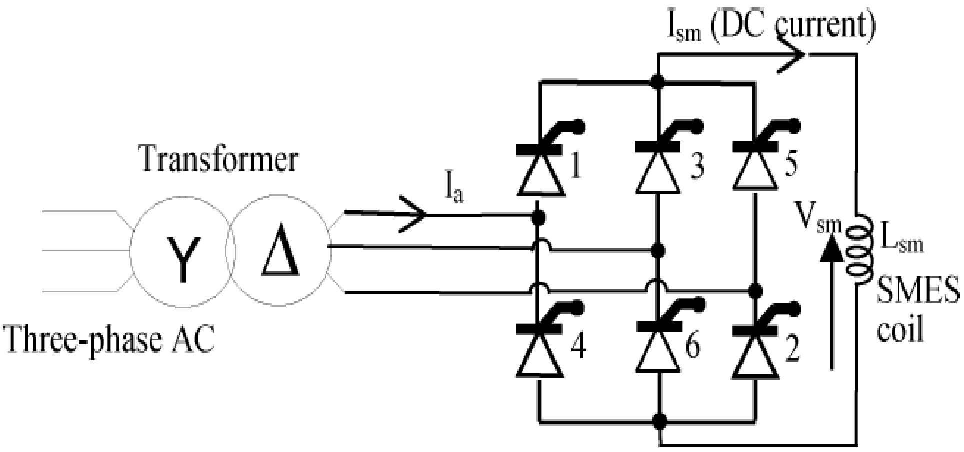

Figure 33- SMES unit with 6-pulse bridge ac/dc thyristor-controlled converter

- **SMES operating modes:**

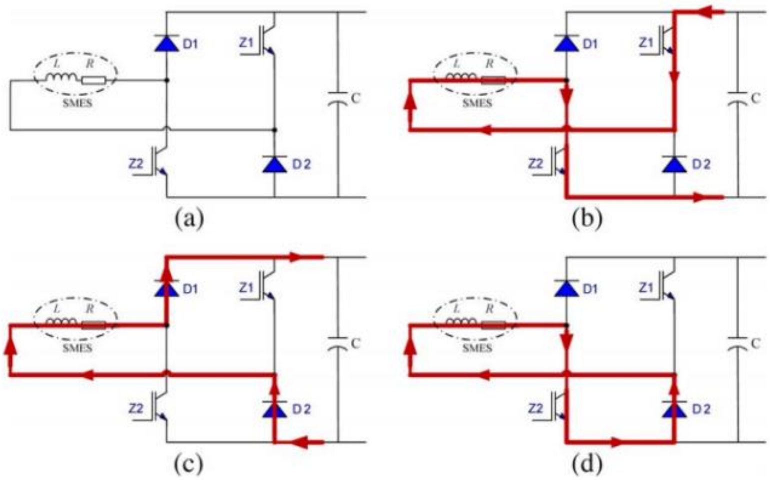

Figure 34- Interface circuit topology of SMES in different states: (a)- topology, (b)- Charging , (c)- Discharging , (d)- Storing

- **Energy Charging Mode**

For a specific inductor, the initial charging current is assumed "I_0" and switches Z1, Z2 are turned on; so that SMES is fully charged if there is an excess power in the main circuit. Thus, the charging current I(t) at time "t" can be expressed by:

$$I(t)=\frac{U}{L}t+I_0 \qquad (18)$$

If I_0=0, the charging circuit is operated at zero-state response state. Then, the charging current I(t) is simplified accordingly [58]:

$$I(t)=\frac{U}{L}t \tag{19}$$

- **Energy Storing Mode**

By keeping the initial current I_0, the storing current (I_{st}) at time "t" might be computed through the following equation [58]:

$$I_{st}= I_0 * \exp\left(\frac{-Re*t}{L}\right) \tag{20}$$

Z2 is turned on and D2 is forward-biased so that the current flows in a closed loop. It has been called also "stand-by" state since SMES inductor is neither charging nor discharging. In that state, the residual stored energy and the voltage across SMES, can be computed by equations (14) & (17) respectively. For a superconductor, Re ~ 0, the internal resistance is neglected. Then, the storing current and residual energy remain unchanged.

- **Energy-Discharging Mode**

This mode comprises of two different modes: Controlled discharging mode & uncontrolled/ natural discharging mode. Generally, the controlled mode might have two states: constant-power discharging mode, varying-power discharging mode [58]. In the uncontrolled discharging mode, SMES behaves as a current source to feed the load resistance "R". Thus, the superconductor discharges its full capacity to that load according to equation (21). The only adjustment is to consider R instead of R_e due to the disappearance of SMES internal resistance through superconductivity state. Referring to Figure 34 (c), switches Z1, Z2 are turned-off while D1, D2 are forward-biased. On the other hand, the controlled discharging mode is a sophisticated state which incorporates the energy-storing & uncontrolled discharging mode together. For $P_{disch}(t)$ = U'(t)*I'(t). If the load voltage/current is lower than SMES voltage/current, the circuit operates in the uncontrolled mode. Unlike the previous condition, energy storing mode is applied when load voltage/current is higher than SMES voltage/current. Then, for a constant-power discharging mode, the discharging current I(t) can be formulated:

$$I(t)=\sqrt{I_o^2-\frac{2}{L}\int \mathrm{P}'(\mathrm{t})\mathrm{dt}} \tag{21}$$

For a constant-power discharging mode, let us consider that SMES discharges its power for a period of T_s which is defined by “constant power discharging time” which is given by:

$$T_s = \frac{\frac{L}{2}\left(I_o^2 - {I'}^2\right)}{P'} \tag{22}$$

If I(t) is reduced to I’(t), SMES won’t be able to supply the load with the same constant power discharge rate. So, this condition effectively affirms the operation of uncontrolled discharging mode. Another interesting factor is “*The effective energy utilization*” which computes the ratio between the time that SMES is actually operating & the total time that it can be operated. This factor can be computed then by:

$$D = \frac{2\, p' * ts}{L * I_0^2} \tag{23}$$

4.5 DC/DC converter

DC-DC converters are composed of two distinct types: PWM and soft-switching converters. PWM switching techniques are preferably used over the soft converters because of its simple control & high efficiency and its high conversion ratios for step-up & step-down applications [52]. An illustration of a DC-DC converter is VSC-Based SMES, see section 4.2. This converter is an essential power equipment for modulating the voltage across the inductance according to SMES requirements. This allows an independent control of active & reactive power flow between the superconducting coil & the power grid. The charging/discharging rate of SMES is controlled by accurate determination of polarity & magnitude of the DC voltage. This results from the coil current direction. If the direction is clockwise, the power is released from the power network to the superconducting coil. On the other hand, the power is discharged from the coil to the grid. This two quadrant DC chopper is suggested for providing an adjustable voltage across the coil terminals. It consists of 2 IGBT switches & 2 diodes. Generally, the voltage, across the coil terminals, is controlled through the variation of duty ratio (D) for both switches.

The duty ratio is given by the following equation:

$$D = \frac{Ton}{T}, \tag{24}$$

- T_{on}: ON-switching time for a switch
- T: sum of ON and Off-switching time

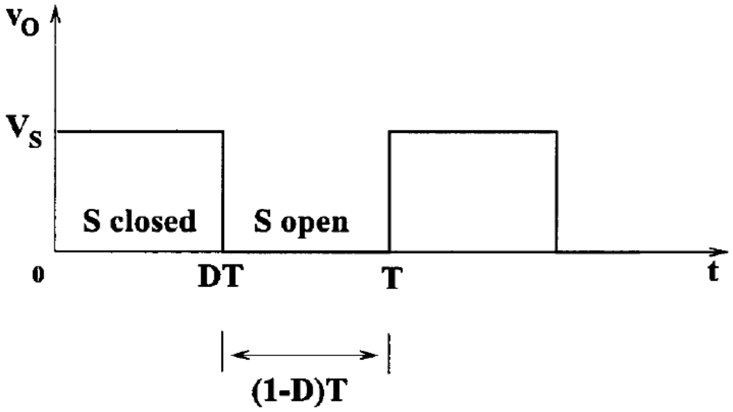

Figure 35- Output voltage waveform for a DC chopper [52]

Other applications of SMES that contribute to the stability improvement of the DC power systems is Hybrid Energy Storage Systems (HESS). This newly developed scheme coordinates between different energy storage systems and a control method called “Dynamic Droop Control (DDC)” is adopted for prioritizing the charging/discharging between SMES & other energy storage technologies. Effectively, this process includes DC/DC converters that unify the voltage across the bus (6 kVDC). In such scheme, several DC choppers are installed. The main target, for HESS, is maintaining a constant DC bus voltage & supply pulse loads from various ESSs. Per shown in Figure 36, a simplified AES including HESS is illustrated. This scheme concerns the power system on ships which are supplied by two main generators; each rated 7 MW, 6.6 KV & 50 Hz. These generators are connected via AC/DC converters to a main DC bus voltage. They are arranged to fulfil the demand for different loads: propulsion, ship service loads, motors, etc. However, HESS is added on the DC-DC receivers to fulfil the required demand by pulse loads (5 MW) in a very short time which cannot be completely met by these generators since their ramp-rate didn’t maintain a full supply to this type of loads. Based on load requirements, SMES size is kept low to avoid an anticipated rise in its cost, see Table 6. The charge & discharge rate of SMES is basically controlled by H-bridge controller as mentioned in Pages (60,61). This rate is usually dependent on two main factors: V_{ref} and I_{smes}. V_{ref} represents the tolerance limits for DC bus voltage while I_{smes} is the current stored in SMES. In **charging mode**, the supply rate for SMES is not a constant value. Thus, it is given as a function of stored current in it. On the other hand, other parameters such as: K_a, K_b, K_{SMES} are adjustable factors that manage the transition period between SMES & battery.

$$Q_1= k_a *exp^{(\frac{Ismes}{Ksmes})^{kb}}, \tag{25}$$

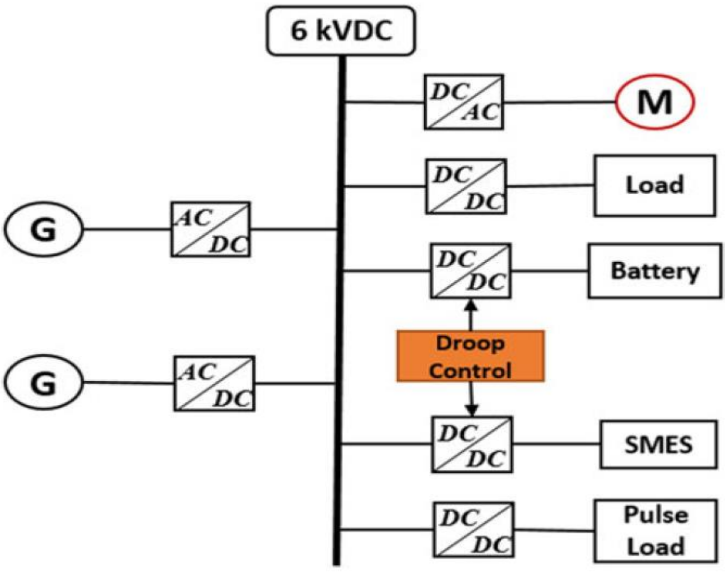

Figure 36- Simplified AES including HESS [59]

Conversely, the rate of discharge for SMES relies on the stored current but the only difference is that this applicable only if the bus voltage (V_{bus}) < $(V_{ref})_{min}$. Thus, SMES releases its power to tolerate the bus voltage around its limits (10%) according to eq. below.

$$Q_2 = k_a * \log_{10}(\frac{Ismes}{Ksmes})^{Kb}, \quad (26)$$

Parameter	Quantity	Value
SMES	1	500 kJ (~ 138.8 Wh), 17.35 kg, 0.69 m^3
BATTERY	1	13.88 kWh, 92.53 kg, 0.0694 m^3

Table 6- Design parameters for propulsion ship [59]

To summarize, Several SMES control configurations were explained & various operation modes are applied. Brief discussion has been made for comparing between different control methods: VSC, CSC and thyristor-based. VSC is selected for SMES applications rather than other techniques. In addition, a simple example of HESS is illustrated to show the convenience of SMES to fulfil the demand in a short time for pulse loads & maintain a constant voltage on DC bus.

Chapter 5. Economic Assessment for Superconducting Magnetic Energy Storage System (SMES)

5.1 General Scope

Using SMES in power system applications have expanded last few decades. The need of such technology has led to an improvement in their employment for mitigating several challenges related to power losses, machine stability, etc. The advent of this technology should be accompanied with a guidance of cost-related numbers that might help on estimating the cost of this technology. Electricity storage system purchases are effectively estimated, in the same way, as other investments. If the cost of energy (€/kWh) < Reference cost, this might be beneficial for proceeding in such project. The reference cost is defined as a specific price of 1 kWh of electricity above which the project becomes unprofitable. Otherwise, different procedures should be applied for achieving a cost-effective project. In Table 7, several technologies are distinguished in terms of capital cost. According to the previous table, SMES cost (€/kW) is inversely proportional with its size. Consequently, high-storage capacity is allowable, for a specific volume, with almost a moderate price as shown in Figure 37. These graphs are based on two experiments conducted for two types of superconductors. One of these plants implement LTS technology and the superconductor is immersed in liquid helium for 1.8 K. On the other hand, HTS technology is applied for a different SMES plant in a liquid nitrogen for 77 K. With an increasing size, there is a high similarity between these two technologies regarding their price. Compared to other technologies, this is an unusual feature which encourages its usage in different applications [27].

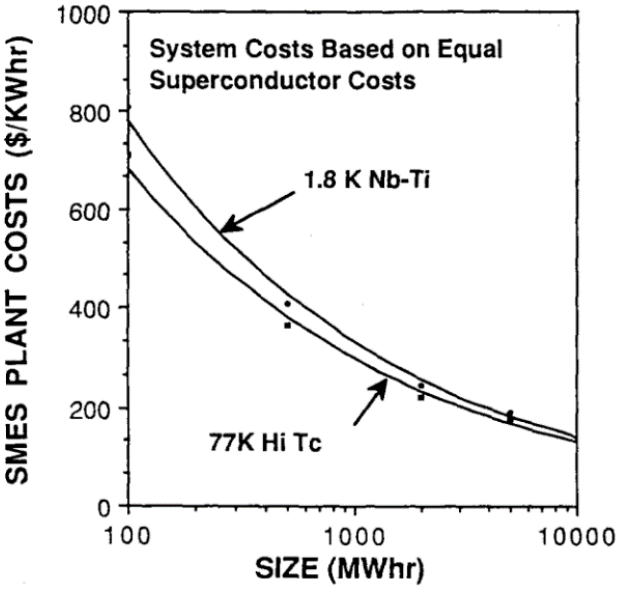

Figure 37- Cost of SMES plants of several size per unit of stored energy [27]

5.2 Capital cost

This term is a fundamental parameter affecting the economic assessment for any ESDs. This includes the essential device's cost (SMES, battery, etc.). It represents more than ¾ of the total cost. Thus, it is a considerable factor which is encouraged in an economic modelling of any storage element. They can be expressed in (€/kW, €/kWh and €/kW per cycle). The capital cost can be used for distinguishing between competing technologies. Suppose that ESDs storage efficiency are given, capital costs are computed. The additional cost per cycle is evaluated after dividing the cost of per unit energy over the life cycle of the ESD. Flywheels & supercapacitors are optimally efficient in terms of cost per cycle as shown in Table 7. On the other hand, batteries are not economically efficient since their life cycle is shorter than other ESDs which result in a higher cost per cycle. Thus, batteries are not a suitable device for such applications that require load levelling. Unlike wind farms, O&M and replacement costs might not be computed in the capital cost since some technologies are under development. It is noted that these typical provided data, in the following table, is a trial which can be adjusted based upon the circumstances: project location, application's type, rating of ESD, etc.

ESD type	Power Rating (kWh)	[€/kW]	[€/kWh]	€/kWh per cycle
SMES	100-10000	200-300	1000-10000	-
Flywheel	0-250	250-350	1000-5000	3-25
Supercapacitors	0-300	100-300	300-2000	2-20
Lead-Acid batteries	0-20	300-600	200-400	20-100

Table 7- Economic evaluation for several energy storage technologies

5.3 Replacement cost

For any storage system or subsystem, specific system's components are subject to damage during the expected life of the system. Then, additional expenses are directed for replacement. This "Replacement Cost" is accounted as a variable cost which means that its value depends on the component size, type & rating. As reported in [60], the total refurbishment cost can be estimated, annually, for the total lifetime for a storage battery. Additional annual charge is considered as a replacement cost escalation (2.5 - 3

%). If the lifetime of a battery is 10 years, then the cost per unit (c/kWh) will decrease by 7%, annually. So, this charge is beneficial when applying these costs.

5.4 SMES cost analysis

After getting a clear understanding about the pricing for different storage technologies. It's vital to illustrate several components that affect SMES cost. The system's cost can be divided into three main components: *Coil*, *Cryogenic system* and *Power Conversion System*. Each of these consist of different elements. SC includes leads, containment, bus and external supports, while cryogenic system comprises of the refrigeration & vacuum vessels. PCI includes: VSI & choppers. Generally, HTS technology is expected to be cheaper than LTS due to the non-required refrigeration system (R). R contributes in 5-10% from SMES overall cost. This type of cost is scheduled as annual cost. Superconducting Magnet (SC) is the main component that contributes to 20-25% from the total cost. In addition, PCI is a necessary element interfaces between SMES & grid. Based on the converter type, its proportion could be changed up to 30%. Then, a complicated power converter must be avoided to reduce the total pricing for a system. Sometimes, a cost-optimization is a necessary step before applying this system into application. Thus, recent power technologies such as multi-level topology are suggested for cost-effectiveness of the power conversion system. Other costs such as: Operation & Maintenance, Vacuum vessels, etc. are not exceeding 45% from the total cost share of SMES (See Figure 38).

However, some parts are imperative to consider for keeping a long lifetime for storage equipment. Then, annual maintenance is important for SMES to achieve higher efficiency. Based on report [28], It's difficult to estimate the cost of SMES components. Then, it's better to illustrate them as cost proportions or in form of equations. In contrary, these cost percentages are not generalized for all study cases. For instance, karasik et al. [61] has conducted a different study, leading to estimated proportions of 30%, 60% and 10% for SC, PCI and R respectively. Basically, SMES total cost is determined according to energy storage capacity. For utility applications, approximate cost of **$ 70 – 100 K per MJ** is considered. The cryogenic system's pricing is estimated $ 15-25 K per MJ. This estimated value is accounted as 25% of the total cost for SMES. So, the cryogenic system size varies based on the cooling requirements. For a micro-application, it's anticipated that (R%) is lower than its corresponding value for a utility application. This approximation is valid where SMES power & energy ratings are considered in the range of 50-200 MW & 50-3000 MJ consecutively. Beyond these limits, it’s difficult to approximate pricing for these components.

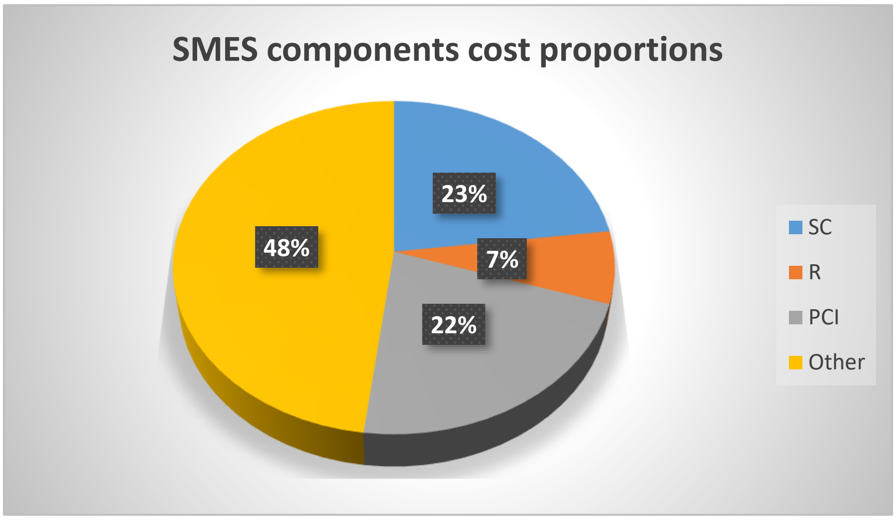

Figure 38- Cost projections of different SMES components [62]

- **Superconducting Magnet cost**

In contrary, other reports provide an empirical relationship between magnet cost & stored energy in the system. These are prominent for a detailed cost assessment. Thus, a trial has been made by Strobridge & his colleagues for estimating the cost of superconducting magnet, as illustrated below [28]:

$$L_{SMES} = 0.844\,(E)^{0.459} \tag{27}$$

- L_{SMES} = Superconducting Magnet cost (M$)
- E = Energy stored in the magnetic field (MJ)

This latter equation can be solved using logarithmic functions. However, since the cost of magnet is given, in that example, which is ~ 23% of the total cost of SMES unit. Then, the unknown variable will be the base of logarithm (E). A trial & error technique is applied to get the value for unknown parameter (E). the graph’s slope’s technique is also employed for this purpose (See Appendix I). Then, X or Y can be simply evaluated. However, the accuracy of this solution is not on the same level compared to numerical analysis. Thus, the numerical method has more scrutiny rather than graphs. In addition, cost estimate for SMES is not possible without a critical determination of essential power & voltage ratings for the hybrid system. Then, SMES can be modelled according to system’s requirement/need. Conversely, an optimization technique is used for achieving an efficient system with low cost. Then, a brief comparison between financial benefits of utility & SMES system cost is illustrated for concluding the utility's return on investment.

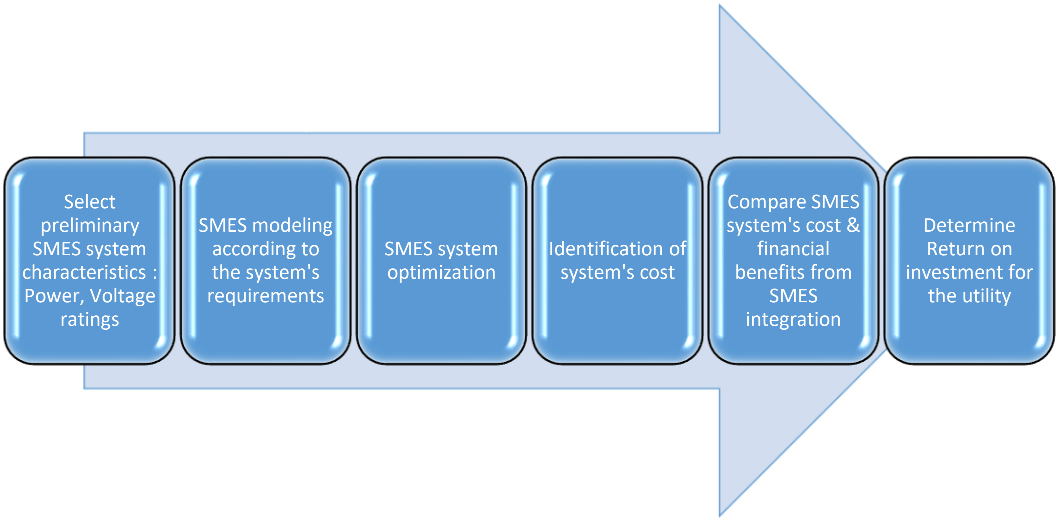

Figure 39- Methodology for a realistic cost estimate of SMES system [61]

In some critical situations such as: transmission enhancement applications, the magnet cost drops-off steeply as a percentage of the total cost of SMES per shown in Figure 40. This is only applicable where energy storage requirements are low; while power capacities are high. For different rated PCS 50, 150, 300, 450 MVA, the magnet cost is decreased 55-60% of the total system cost which is the highest range of reduction in SC.

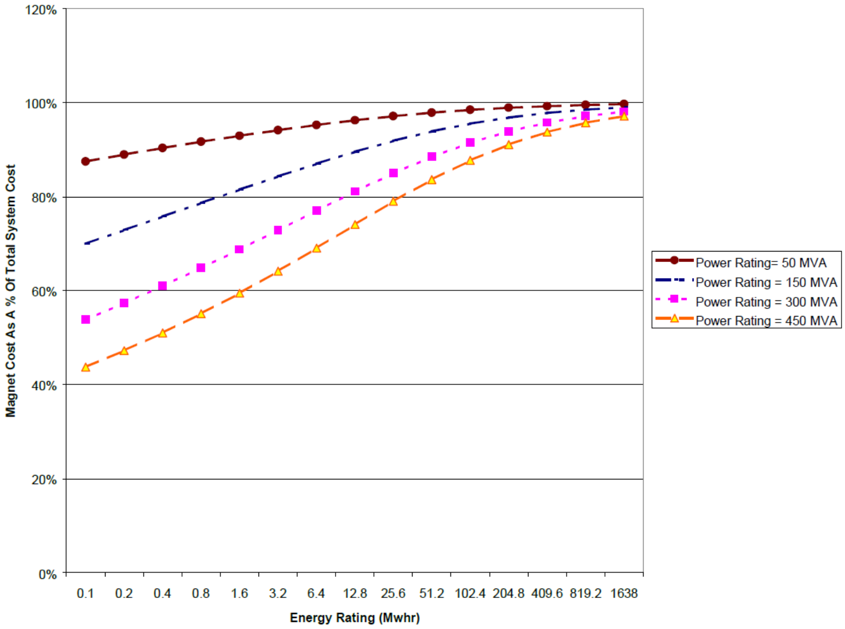

Figure 40- cost of magnet system as a percent of total SMES/FACTS system cost [10]

- **Converters cost**

As shown in Figure 38, most of SMES components are generally considered in terms of proportions due to the difficulty for estimating their values. However, it's still possible to present these parameters in form of equations. For the PCS and converters, DC capacitors are mainly used for power transfer from/to grid based on the system requirements. Then, they are essential elements & their price differs according to the type of converter used.

$$C_{conv} = (C_{sw}+C_{aux})\, P_n \quad , \tag{28}$$

Where,

- $\mathbf{P_n}$: rating of the converter in VA
- $\mathbf{C_{sw}}$: cost per unit VA of the power-electronic switches
- $\mathbf{C_{aux}}$: cost per unit VA of the auxiliary components such as filters and snubbers circuits

For DC-DC & AC-DC converters, a value of 40 €/kVA is assumed. In contrary, the auxiliary components vary based on the type used. In AC-DC converter, C_{aux} is estimated 5 €/kVA, while this value decreased to 0.86 €/kVA for Dual Active Bridge (DAB) converter. The difference in price comes from the fact that no filtering is required for AC voltage waveform in DAB while it's required in AC-DC converter [17]. An example of SMES converter installation is proposed to show the effectiveness of such intermediate equipment in power transfer capability.

- **Refrigerator cost**

The economic evaluation for the refrigeration system is determined through identification of its components cost in the past. As a contrary, the annual cost of refrigeration might be assessed as a function of its refrigeration capacity(kW) & the price of electricity (€/kWh) as shown below.

$$X(M\$) = 2.72\, (R)^{0.78} * (P)^{0.56} \tag{29}$$

The equation is only applicable for a limited refrigeration capacity of 0.04 – 30 kW. Otherwise, the range of electricity cost per kWh is assumed 0.04- 0.18 $. The maximum limit of energy cost will be considered ~ 0.18 $. Then, the annual cost of refrigeration will be equal to 84.5 k$. 22% of the refrigeration capital cost is required for maintenance & operation, amortization and depreciation.

5.5 Economic Benefits

The illustration of the principle equations; governing SMES operation is not only enough to implement an economic assessment. Cost saving is an elementary factor that is considered before executing a hybrid system including SMES. This cost saving is an indirect form of revenue that reduces the expenses over a long time. As reported in [62], two DC interconnected system with storage installations are better in terms of cost rather than exploitation of SMES only in power transfer from/to grid. This study shows that a combined use of SMES storage element with a different energy storage technology such as: battery, super-capacitor or flywheels achieves cost reduction with 20%. Compared to sole operation for SMES, this cost saving is much impressive. Thus, it's proposed to use back-to-back DC link installations with combined storage technologies for obtaining a maximum profit. This technique might be applied for BESS and this proved a cost reduction from 12 - 18 %. However, it's lower than SMES combined system's proportion due to the variation of battery's efficiency over SMES. SMES exhibits higher efficiency of 95 - 97% compared with 74% for batteries.

- **Main actors of power system**

  Due to the integration of high numbers for RES into the power system, several challenges are emerged due to multiple impacts on the energy market, consumption behaviour, supply policy for states and society. A recent study is built upon a survey which is conducted to assess the main influential actors with a fast integration of RES into power system. The majority of participants are in research area while the minority involves NGO members, policy makers, analysts, etc.

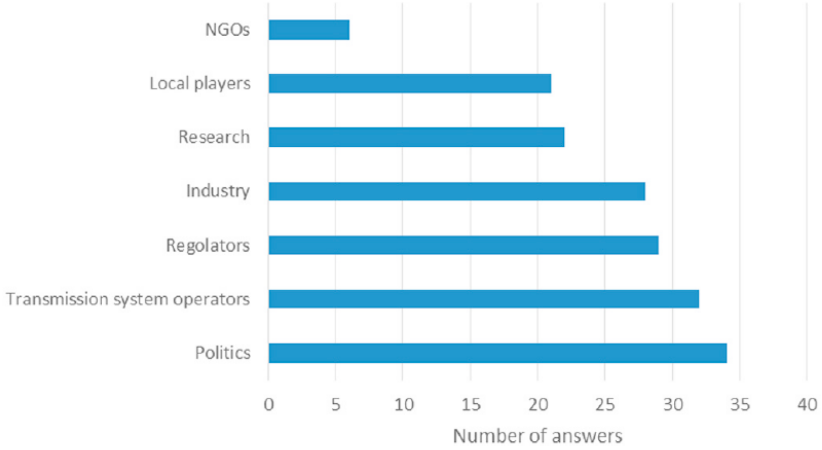

Figure 41- The most influential actors in a power system network with a high portion of RES including SMES storage elements [63]

Per illustrated in Figure 41, politics is among the most influential actors in the power system due to the importance of policy-makers in framing a deeper study in policy impacts of these new renewable sources integration & regulating the market according to these new technologies. Consecutively, TSO, regulators and industry are involved for a general comprehension of the economic & technical evaluation for such technologies. Then, it comes the opportunity for researchers & local players to demonstrate RES development & their necessity; in the main power system network, for the environmental pollution reduction & RES growth [63].

5.6 Reassessment of SMES studies

In this part, a review of SMES benefits, from an economic point of view, will be illustrated. Before discussing that, common economic parameters are used for indicating the benefit of such a technology. For instance, Net Present Value (NPV), Return On Equity (ROE). These results have shown that the application of SMES for transmission enhancement achieves positive net present value. In addition, power quality enhancement is not the sole application for SMES. Back-up storage for industrial customers is also another profitable project based on [10]. Generally, NPV is an economic terminology used for capital budgeting to determine which project is profitable in the long term. A positive result means that this project is going to have profit, in the future, compared with the initial investment. However, a negative result reflects that a specific project is valueless. Another study had investigated the potential benefits of SMES on a utility transmission system. The power transfer capability is increased, the most, when SMES size is 300 MW. In this situation, NPV will get a maximum value. Consequently, it's recommended to install a large size for SMES in such applications for having maximum profits. Despite these advantages, SMES is not cost-effective for single purpose applications. Thus, it's suggested to apply it for multiple benefits as explained in section 1.1. In the next example, A SMES; with 500 MVA capacity & energy ratings of 1 MWhr, is also studied. Some of its benefits concern the reduction of spinning reserve, load levelling & decrease in under frequency load shedding. Conducted results are favouring SMES development since high NPV is proved for that unit. Compared to initial cost of $45-80 M, the economic NPV is rated $100-140 M which encourages its employment in a wide range. This is also considered as an indirect type of revenues since the investor will get profit after several number of years when an excess of storage happens. Then, he becomes a power producer & it's possible to sell power with a considerable price.

Benefit	Unit value ($x million)	Net Present Value ($x million)
Transmission Enhancement/yr.	5-7	69-92
Under frequency load shedding	2-6	3-16
Spinning reserve/yr.	0.07	0.94
Total		**100-140**

Table 8- Summary of 500 MVA (1 MWhr) SMES

In other words, this stored power can also be sold to the main utility & a reward is indirectly expected in form of reduced electricity bill. The total present value is an approximation because most of SMES benefits are given in form of price ranges, not accurate values, as shown in the previous table [10].

- **Study Case**

  A recent study has been conducted, with help of Electric Power Research Institute (EPRI), for assessing the benefits of SMES to improve the transmission capability for Arizona – California TL. A SMES unit rated 475 MVA has achieved tremendous improvement in the transferred power up to 500 MW, if thermal conductor & voltage limitations were resolved. Compared with larger unit of STATCOM “675 MVA”, small SMES unit could be installed, instead of other reactive power compensators, for the same objective. This demonstration shows that SMES installation, in some critical situations, is much beneficial & achieves more efficiency rather than STATCOM reactive compensator installation with bigger units. That’s also an indirect form of revenues SMES system. Then, this situation is an ideal application for SMES & would be interesting for investors to deploy their investment in these technologies [10].

Synthesis summary

Finally, an exhaustive economic study for SMES is unveiled. Furthermore, an economic evaluation for several energy storage technologies is shown. In addition, a cost proportion comparison for SMES components is exhibited for identifying the most expensive component in SMES device.

Also, this helps on optimizing the cost of SMES for several industrial applications. In the end, a general methodology is illustrated; for a real cost estimate of SMES. Also, the main actors; which have an impact; in the power system are enumerated. Then, a complementary study has been deduced for showing SMES benefits on the enhancement of transmission power capability.

CONCLUSION

With respect to other storage technologies, SMES is considered as one of the impressive solutions for power system stability. They are widely used because of its higher efficiency ~ 95% & fast charging response, it can compensate a specific demand in a very short time. Then, it could be used as a secondary back-up for some industrial applications. However, some applications; which require long-term storage, necessitate the installation of other technologies such as batteries due to its higher power density compared to energy density. Additionally, the power flow control from/to grid has been maintained through an intermediate power electronics device (Converters/inverters). Based on the conducted study, VSC is much suggested for operation with SMES rather than CSC and thyristor-based because of its minimum losses in different P.E switches. Further, CSC provides more capacity capability but requires additional spaces which is reflected to supplementary cost. This can be avoided through using a cheaper equipment (VSC) with a simple configuration. Regarding the economic evaluation for SMES system, a critical comparison has been made for several power ratings, the cost per cycle is computed as an indicator for selection between technologies that are economically efficient. Flywheels, for example, are not recommended since it has high cost per cycle for a lower power rating. In contrary, SMES components are estimated as a percentage of total SMES cost, in majority of applications, because the uncertainty associated with their installation. In some projects, cryocooler devices are suggested to be bigger than other units & SMES is installed in a smaller size. Ratings of equipment & type of project have also an effect on the determination of SMES components values. Furthermore, the energy stored in SMES is a variable parameter that must be considered. As shown in last chapter, empirical relationship between the magnet cost & its stored energy is given which means that SC cost varies according to that. For converters & refrigerator costs, they are also function of other parameters such as: price of electricity (€/kWh) & refrigeration capacity. As reported in several studies, SMES integration with other storage technology has achieved more economic optimization compared with sole installation of SMES. Also, the main contributors, in a power system, are mentioned for HESS microgrid. This should be pinpointed to understand how the market of RES is influenced and the policy regulation for this de-regulated network. Finally, a case study of SMES application has been demonstrated to show the effect of SMES on enhancing the transmission power capability on the main T.L “Arizona-California”.

Appendix I

- **Spinning Reserve (SR)**

  All electric utilities must attain some basic requirements for successful operation. Affordable generation capacity is provided as an extra source and can respond in 5-10 minutes for any power outages. SR is normally adjusted on “Stand-by mode” and remain unloaded until needed. If any generation unit is failed, SR becomes on-line and compensate all loads connected to the failed generating unit. The minimum available reserve power is determined based on the capacities of generation units. Conventionally, SR should be, at least, equal to the output power of largest generating unit on operation. SR is also known as “Reserve services” since it affords a reasonable control for the utility. Two types of reserves are available: Fast reserve, Short-Term Operation Reserve (STOR). The discrepancy, between both services, reveals on time-of-service operation and the capacity of delivered power. In fast reserve, the delivered power can attain 25 MW and this should be sustainable for a period of 15 minutes. Conversely, the power delivery rate for STOR is limited to 3 MW but it could be sustainable for a minimum of 2 hours. Although the previous advantages of SR, supplemental & back-up supplies are strongly suggested to provide a secondary supply for the interrupted load if the main supply, SR ran out of energy. But, the back-up supply begins to supply a load within one hour. On the other hand, additional supplies are like SR for the intervention time while keeping in mind the deviation from the grid frequency.

- **Advanced Battery Energy Storage Systems [Zn/Br]**

  Among several battery technologies, Zinc-bromine battery is an impressive technology which is mainly employed for electric-vehicles & utility energy storage. However, this technology is a promising solution since it shows a good efficiency and doesn’t require high investment cost. Typically, Zn/Br battery is normally operating on the range of 20°- 50°. The operating temperature has an adverse effect on the system efficiency. The most significant factors; influencing the lifetime of this battery technology, are related to the degradation rate of zinc-bromine battery components. If this rate is negligible, the battery will have a longer lifetime compared with other technologies. Otherwise, the battery might be damaged in the short-term.

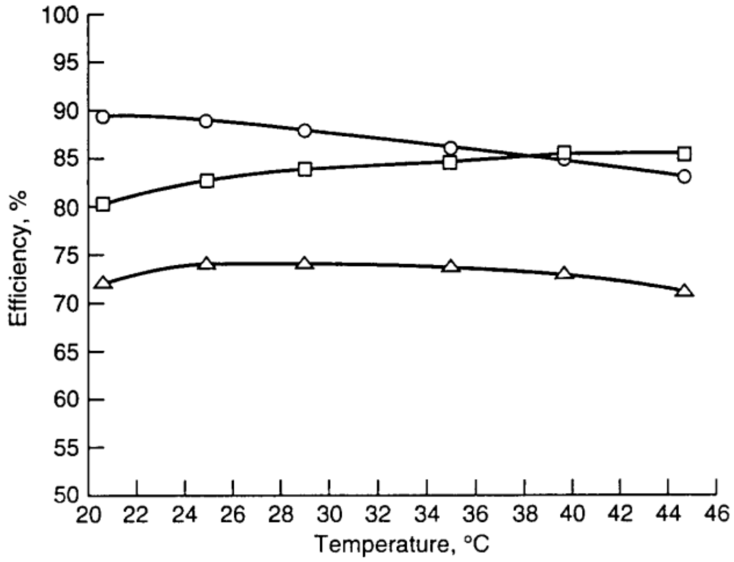

Figure I'- Energy efficiency Vs. Operating temperature for Zn/Br battery [∆: Energy ,○ : Columbic, □: voltaic]

- **Discount Rate Vs. Net Present Values (NPV)**

  As discussed previously, NPV values for a specific project are mainly related to the rate of return. Since the latter value is determined by the investor. So, these values are considered Variables. It's usually preferrable to select lower discount rate for getting higher NPVs.

I (rate of return)	*5*	*6*	*7*	*8*	*9*	*10*
NPV (Net present value) K$	*615*	*558*	*503*	*451*	*401*	*353*

Table I'– NPV values for different rate of return

- **Magnet Cost Vs. Stored Energy**

For SMES cost assessment, it's difficult to obtain the magnet cost; without the previous knowledge of the stored energy capacity of SMES, as mentioned in section 5.4. Some equations govern these relations. However, the following figure is a helpful tool to obtain the stored energy if the magnet cost is given or vice versa. These equations are available for different coil arrangements. Based on the system requirement & coil design, the equation is selected. Then, the magnet cost differs from an application to another, according to this condition. Some results are obtained using these graphs & compared with equations, in the last chapter. In addition, the coil magnet used is often different from a project to another. Thus, several magnet types are shown with their corresponding equations. So, we might say that these curves are approximate & not exact.

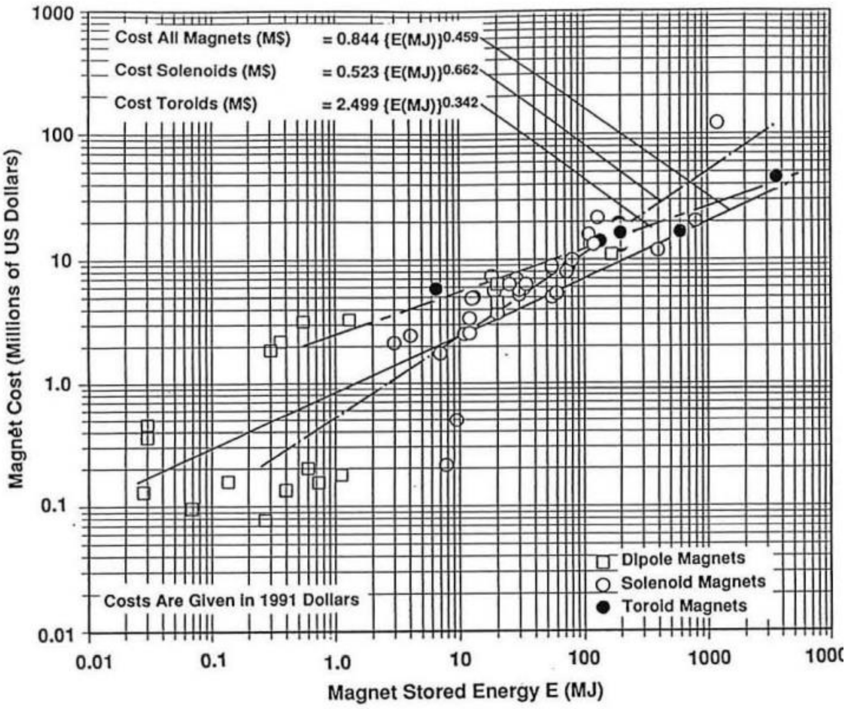

Figure 8'– Superconducting Magnet cost versus magnet stored energy

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