Technical Approach for the Inclusion of Superconducting Magnetic energy Storage in a Smart City

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Abstract: Smart grids are a concept which is evolving quickly with the implementation of renewable energies and concepts such as Distributed Generation (DG) and micro-grids. Energy storage systems play a very important role in smart grids. The characteristics of smart cities enhance the use of high power density storage systems, such as SMES systems. Because of this, we studied the possibility of adapting these systems in this kind of electrical topology by simulating the effects of an energy storage system with high power density (as SMES). An electrical and control adaptation circuit for storing energy was designed. The circuit consisted of three blocks. The first one was a passive filter LCL. The second was a converter system that allows rectifying of the signal when the system runs in charge mode but acts as an inverter when it changes to discharge mode. Finally, there is a chopper that allows the current levels to be modified. Throughout simulations, we have seen the possibility of controlling the energy supply so as the storage. This permits to adapt to different contingencies which may induce the wiring of the charge in the net, as well as different types of charges. Despite the technical contribution of this kind of systems in the Spanish electrical network, there are big obstacles that would prevent its inclusion in the network, such as the high cost of manufacturing and maintenance compared with other cheaper systems such as superconductors or the low energy density, which limits their use.

Keywords: energy storage; superconducting; adaptation system; smart city; simulation

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Nomenclature

BSCCO	Bismuth Strontium Calcium Copper Oxide
CAES	Compressed Air Energy Storage
CPLD	Complex Programmable Logic Device
DFACTS	Distributed Flexible AC Transmission Systems
DG	Distributed Generation
EDLC	Electric Double Layer Capacitor
ESS	Energy Storage System
EU	European Union
FES	Flywheel Energy Storage
HV	High Voltage
HTS	High Temperature Superconducting
IGBT	Insulated Gate Bipolar Transistor
LTS	Low Temperature Superconducting
LV	Low Voltage
MCU	Micro Controller Unit
MPLS	Multiprotocol Label Switching
MV	Medium Voltage
NbTi	Niobio-Titanio
PHS	Pumped Hydro Storage
REBT	Reglamento Electrotécnico de Baja Tensión
REE	Spanish Electricity Network
SMES	Superconducting Magnetic Energy Storage
YBCO	Yttrium Barium Copper Oxide

Symbols

T_c	Critical temperature
L_{SMES}	Coil Inductance
$L_{1,2}$	Inductance of filter coils
C	Filter capacitor capacity
I_C	Maximum current in the filter capacitor
I_O	Rated filter current
ω	Frequency of the grid
ω_{res}	Resonance frequency
ω_{con}	Switching frequency
THD	Total Harmonic Distortion
C_1	Capacity of the rectifier capacitor
V_o	Average voltage in the rectifier capacitor
Δv_o	Curing of the voltage allowed in the grinding capacitor
R_{eq}	Equivalent resistance seen from the coil
$U_{1,2,3}$	Input voltage to the converter
$i_{1,2,3}$	Input current to the converter
U_{DC}	Voltage at the rectifier capacitor terminals
i_{SMES}	SMES coil input current

1. Introduction

A smart grid is a concept that has evolved quickly with the implementation of renewable energies and concepts as distributed generation (DG) and micro-grids. According to the electricity system operator in the Spanish electricity network, REE, a smart grid [1] is "one that can efficiently integrate the behaviour and the actions of all the users connected to it, so that it ensures a sustainable and efficient energy system with low losses and high-level quality and supply security".

The definition given by the REE of Smart grids encompasses both the electrical system and the communications system. The main idea is to synergize efforts and capabilities to improve the system so that it allows optimal results to be obtained, despite the complexity of factors and entities acting in the electrical network.

Within that concept and in the electricity supply networks of the near future, we may find the concept of smart city, which can be defined as those cities that already have an innovative system and networking to provide an improved model of economic and political efficiency allowing social, cultural and urban development. To support this growth, there is a commitment to innovation industries and to high technology, which permits urban growth based on the impulse of capabilities and networks. This will be achieved through strategic and inclusive plans that enable the improvement of the local innovative system [2].

Nowadays, the focus is on the development of models that permit to increase the efficiency of the elements which electric network has towards cities. This is based on statistics and data that shows that 54% of the world's population lives in cities. This percentage will increase, not only owing to the migration of the rural population towards cities but also by the growth of the population. It is estimated that in the next 25 years, the world population will increase from 7300 million to 9500 million people and that the population will be more urban, increasing to 66% in 2050 [3].

This urbanization process is even more advanced in Europe and particularly in Spain, in which more than two-thirds of the population is urban and is expected to reach 85% by 2050, which, along with the American continent, leads this population change [3].

The model of the electricity system by means of DG allows to diversify generation systems and adapt them to temporal or geographical needs. This model promotes renewable generation systems of low and medium power. This is associated with the use of energy storage systems (ESS).

Besides traditional storage systems, such as different types of batteries or compressed air systems (CAES), there are other systems such as flywheels and Li-ion batteries; and supercapacitors or Superconducting Magnetic Energy Storage (SMES), which might face system's requirements with high power density energy storage.

The use of SMES systems in smart cities provides an element of support to zones in which peak power is required at certain times, such as in industrial areas. Furthermore, SMES systems can provide other applications, which enable its inclusion in the network, such as Uninterruptible Power Supplies (UPS), adequacy systems of voltage levels and frequency control.

The inclusion of an ESS in the electricity network in a Smart city complements the use of renewable generation systems because these systems could bring distortions in the quality of the network signal. Therefore, a DG system is related to ESS, which implies different possibilities in the connection to the network, as will be seen during the article.

The present article is divided into 6 sections. In addition to the introductory section, the methods and materials used in this article will be explained in section 2. In this section, section 2, the actual electric network model will be presented followed by distribution grid settings of the ESS towards the reference distribution grid. In the section 3, the theoretical framework concerning the inclusion of storage system SMES in a Smart city is explained. This allows to obtain possible benefits of the inclusion of these systems on the electric network, so as another type of indirect profits. In the section 4, the results are shown according to simulations performed following the methodology and calculations indicated in the previous sections. In this section, section 4, obtained signals in the inlet and outlet of the converter during the charge and discharge of these systems are shown.

The discussion of the results obtained in the section 4 at a theoretical level as well as the analysis of the different architectures of the network are presented in section 5, considering the characteristics and main assumptions developed earlier. Finally, in section 6, the main conclusions learned throughout the technical study of the inclusion of these systems in a smart city connected to the Spanish electric network will be presented.

2. Material and Methods

In this section, we describe the processes we carried out during this study to obtain the results. The analysis of the electricity network is one of the most important aspects in this process and, also, the main point.

We have to keep in mind that the actual electricity network in the Spanish system is based on a pyramidal structure. Currently, energy is mainly generated in big production centres, such as thermal power stations, hydroelectric power plants, and nuclear power plants. Energy is carried at a HV until it reaches the distribution grid and final consumers, Figure 1.

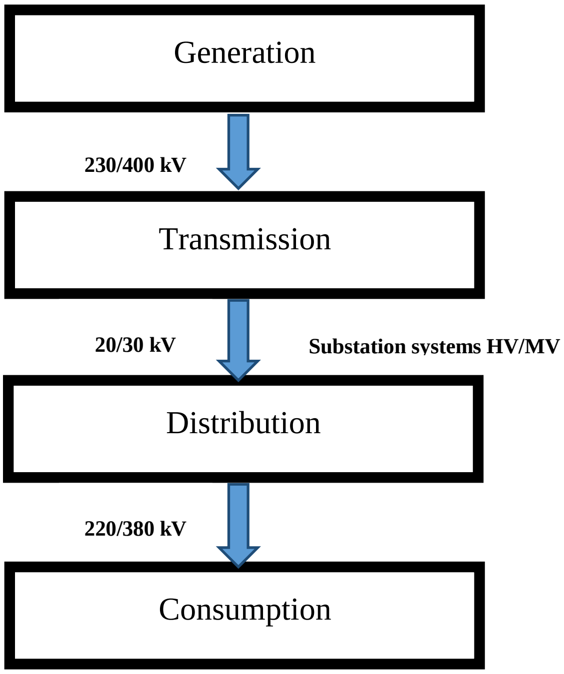

Figure 1. Model of the Spanish electricity grid. Source: Adapted from [4].

In the last years, this structure has started to change owing to the inclusion of small generation centres in the network, which has been empowered by the expansion of renewable energies. This is possible thanks to a meshed grid with distributed generation, a concept which is very much linked to smart grids, Figure 2. The use of cogeneration systems that allow the generation of district heating and electric generation systems is also enhanced [5].

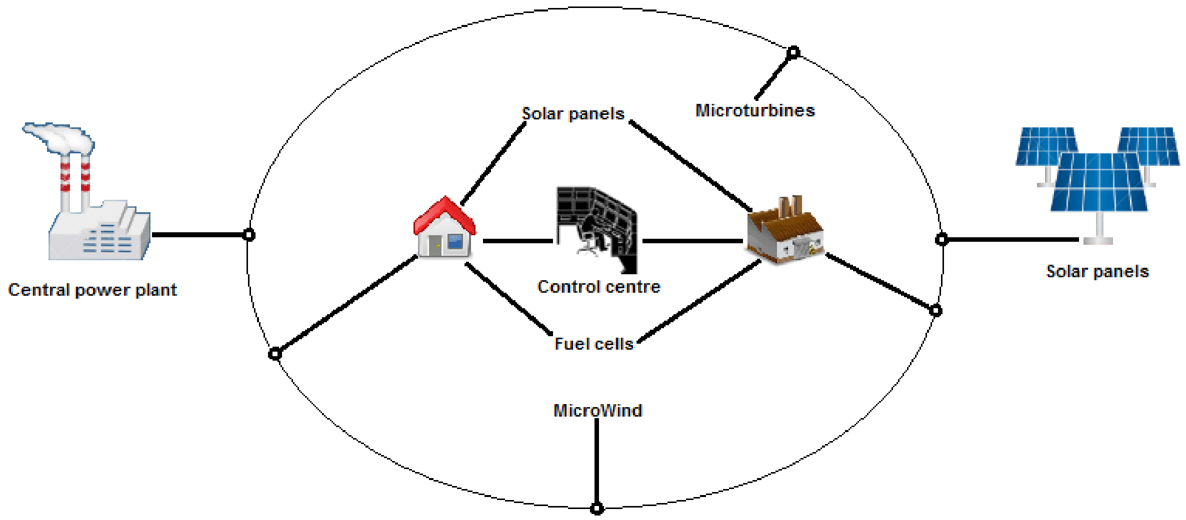

Figure 2. Distributed Generation Model. Source: Adapted from [6].

In the new electricity grid model, renewable generation sources play a very important role. In addition, renewable energies are linked systems, such as ESS, that enable proper operation in the electrical system.

In relation to ESS, it is important to consider that storage systems can act in two ways. On the one hand as loads in the network when they are in charge mode, and on the other hand, as generators when they are in discharge mode. The connection of these systems to the network can be done at any point of the network. In the study, we focused on network transport at MV. Figure 3 shows a basic scheme of the SMES System.

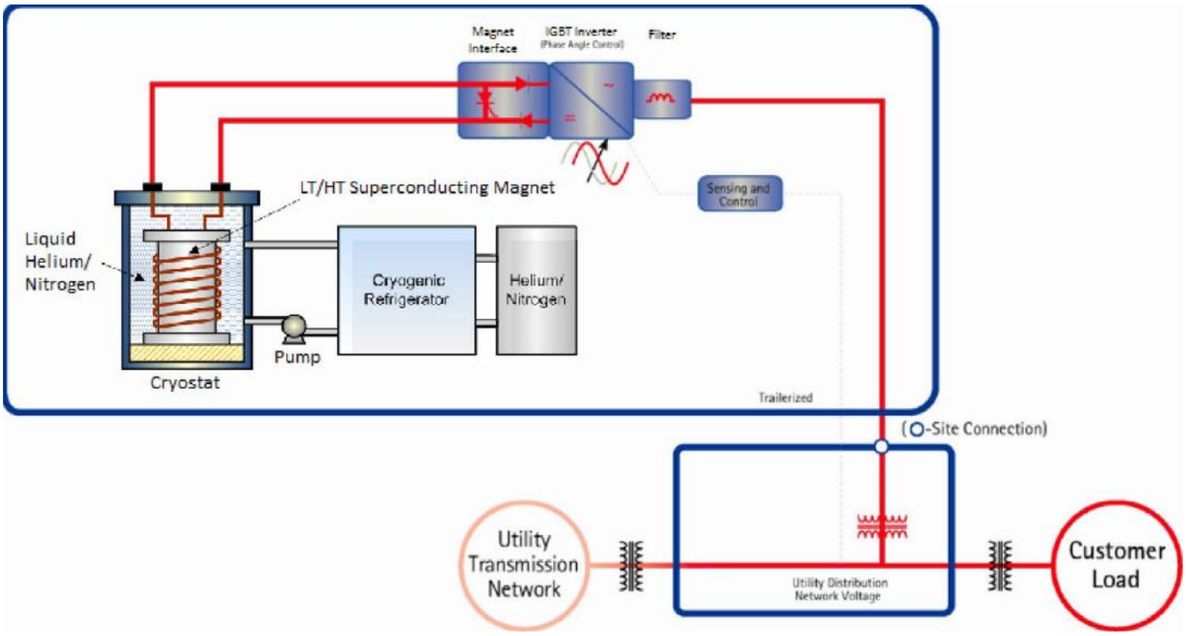

Figure 3. Basic scheme of a SMES system [7].

For the connection of the ESS of the terminals normalized in the transformer is ΔYn11, that is to say, the primary voltage from the transformer goes in a triangle and the secondary in star, with an accessible neutral terminal in order to power the various receivers and also to connect for electrical grounding the neutral point of the secondary. The secondary voltage of the transformer, which is normalized by the European Union [8] (EU), is 400 V between phases and 230 V between phase and neutral for supplying final user in the distribution grid.

With the aim of understanding the behaviour of the SMES system in the network, the data of the study conducted by [9], in which there is a SMES system Energy/Power=6,49 MWh/1,52 MW, with the idea of being able to simulate the circuit by means of the program Proteus 8.3. With these indications, it was determined that a secondary voltage of 2000 V from the transformer and a coil current of 325 A are required to obtain the required power requirement.

In this case, it is considered that we work both in primary and in secondary voltage with MT. For this reason, voltages have to be over 1001 V (doing so we intend to mark an initial limit of medium voltage). The aim is to limit the current in every electrical and electronic devices for the purpose of reducing losses. Also, this implies working with elements with huge voltage drops, something to bear in mind while designing the rest of the circuit, especially considering semiconductors.

With these premises, a circuit has been designed that seeks to adapt the network signal to the working of the SMES system. The circuit shown in Figure 4 has been configured, where it is divided into the filter, converter, chopper and SMES coil. The calculation for obtaining the characteristic values of the components is developed in Appendix A.

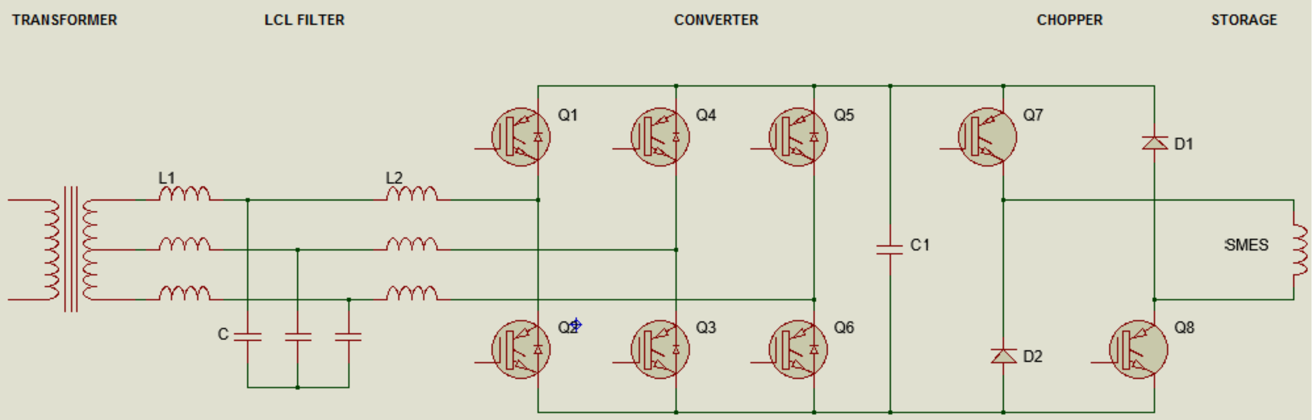

Figure 4. Storage System Circuit. Source: Adapted from [15].

For the design of this circuit has taken into account the working frequency of the grid in Spain, 50 Hz, for the design of the LCL filter placed after the transformer. That transformer will be designed to bear the operating power of the system and will also act as a protective element both in the input and in the output, because it acts as an overcurrent limiter.

In relation to the design of the converter, two main points were considered. The first one is if the converter in rectifier mode can or cannot be controlled. Due to the simplicity of the design and the little importance in the simulated system, we chose the uncontrolled system throughout power diodes. The second point are peak voltages to work with. It is important to keep in mind the voltage design selected in order not to work with higher voltages than the breakdown voltage of the IGBT's and from the rectification capacitor. This can be applied with the IGBT's of the Chopper.

As for the simulation, to obtain the graphs of the corresponding signals, voltage and current probes have been placed at the input of the coil to see its charge and discharge. This probes of Proteus are also provided which show the voltage and current signals to the rectifier input. For this simulation, power losses in transformers, wiring resistances and others elements influencing the measurement of the characteristic values of the SMES system have not been taken into account.

It is important to point out that for the study realization we dismissed samples taken during a second, t=0-1 s. This is mainly due to the lack of a smooth start circuit, which prevents undesired fluctuations to appear during the boot.

3. Theoretical Framework

In this section, we analyse the theoretical framework of the network and the ESS in which the present research was performed. To do that we are going to analyse one of the main smart cities in Spain, Málaga [10].

In appendix B, a smart cities analysis along with SMES storage systems and control and monitoring systems are shown. The interconnection of all the network elements is indispensable in Smart grids.

It is important to keep in mind that nowadays cities occupy 2% of earth surface, consume 75% of world energy and generate 80% of greenhouse gases [11].

A model that encompass the main aspects of a smart city is shown in Figure 5. Within these aspects, we may find transversal elements, such as:

- Information and communication technologies
- Sensors
- Security
- Materials

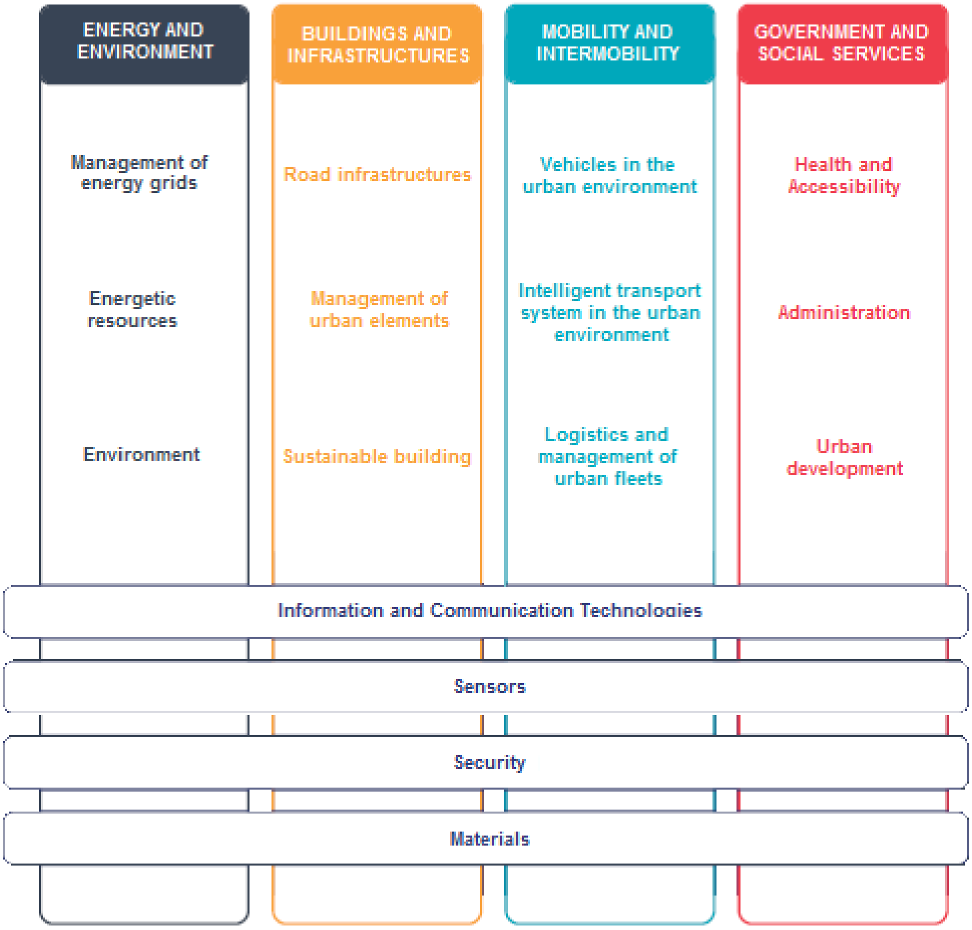

Figure 5. Smart city model. Source: Adapted from [3].

Inside transversal systems is the concept of information and communication technologies, which allows information interconnection among different systems. The communication system of the project smart city Málaga is shown in Appendix C, [10] which displays the interconnection of the different nodes and transformation centres; the communication nodes mostly match with the centres.

There are also 4 blocks to focus on when developing a Smart city: Energy and environment, buildings and facilities [12], mobility and inter-modality and government and social services. All these blocks are connected, they are not isolated. Inside the first block, Energy and Environment, one important element in the smart city is the energy storage systems, ESS, whose main purpose is to guarantee energy supply. Energy storage systems (ESS) can be grouped according to different characteristics which facilitate the choice of one device or another for the storage system [11]. Devices that actually are commercialized and/or in development are grouped in four main groups:

Electrochemistry (different kind of batteries), Mechanic (FES, PHS, CAES), Electrical (SMES, EDLC) and Thermal.

Most of the electricity storage across the world, approximately 95-98%, is based on PHS owing to the simplicity and maturity of this technology. Nevertheless, the number of ESS that are different from PHS has grown from less than 1% to more than 1,5% in 2010, and 2,5% in 2015 (a growth rate higher than 10%) [13, 14].

As stated above, the present article focuses on superconducting magnetic energy storage (SMES), and the technical possibilities of its inclusion in a Smart city. We have to keep in mind that superconducting magnetic energy storage is a system that allows the storage of energy under a magnetic field thanks to the current going through a refrigerated coil at a temperature under critical superconductivity temperature, Tc. The system is based on a superconducting coil, a refrigeration system that allows the critical temperature to be obtained, an electric system to convert and adequate the signal and a control system to adapt currents and optimize the process.

In order to develop these systems and reach the proper working levels, a lot of studies have been realized about performance optimization of these systems, as well as network connection settings [15-22]. Other studies deal with optimization of the electrical adaptation elements, as well as in regulation and control systems [23] or the study of inclusion of these systems in the microgrids/smart grids [24, 25].

4. Results

In this section, we present the results of simulations realized through the Proteus program. It is divided into two subsections. The first one shows signals obtained during the charge of the device, using a converter in rectify mode, both in the coil and in the other entry of that rectifier.

Once the coil charge is simulated, the second subsection shows the signals obtained during the discharge of the SMES system to the network, showing the signal at the terminals of the SMES coil and at the output of the inverter in inversion mode.

4.1. Charge of the Storage System

To carry out simulation in the charge mode, we set the circuit with the non-controlled three-phase full wave rectifier. The circuit has been designed with the calculations shown in Appendix A.

The input voltage to the rectifier, with the 3 phases differenced and out of phase by 120°, is shown in Figure 6. The peak voltage of the waves is at 2828 V with a frequency of 50 Hz. Trials have been carried out, introducing noise and interference, with the intention of verifying the efficiency of the LCL filter design adapted for the case, showing at all times a perfect sinus signal at the entry of the rectifier.

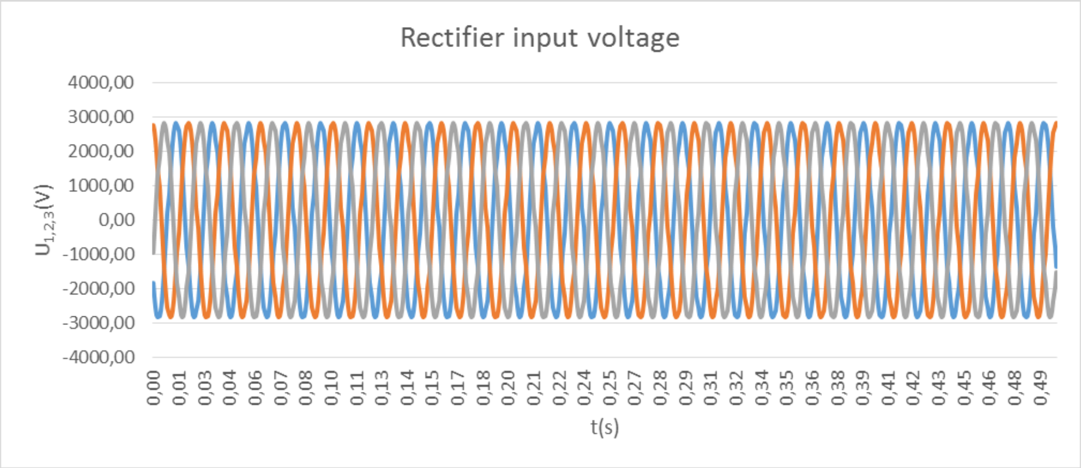

Figure 6. Signal to rectifier input. Source: Own elaboration.

On the other hand, there are input currents in the rectifier. This is shown in Figure 7, where charge moments can be distinguished and when t = 0.36 s, approximately, permanent mode is reached. At this time, the control system considers the ESS charged, consequently the system will disconnect from the rest getting into permanent mode.

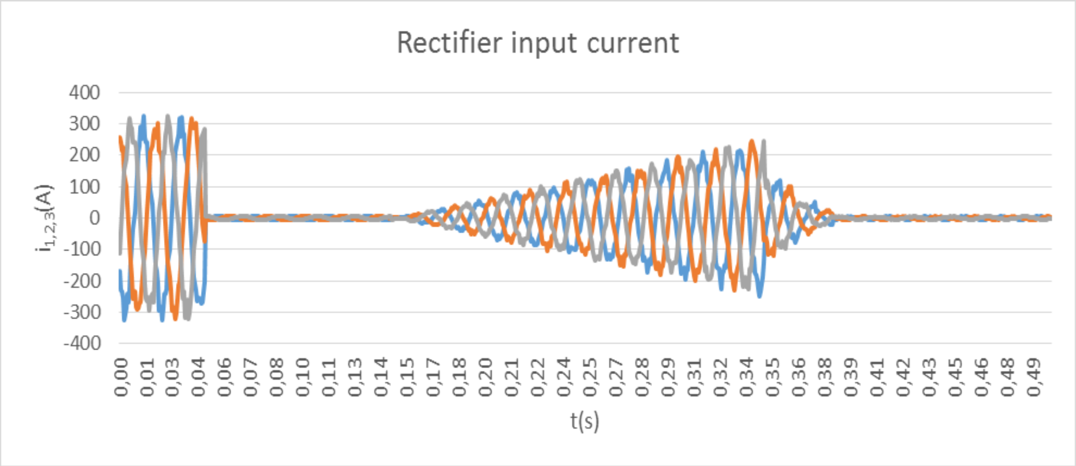

Figure 7. Current at the rectifier input. Source: Own elaboration.

Furthermore, we have to bear in mind voltage and current signals in the SMES system. In this case, as shown in Figure 8, the voltage reached after rectification of full wave is 4600 V after the charge period. Also in Figure 9 it is shown the slope given by the current in the coil during the charge, reaching approximately 325 A. This current is regulated and adapted at each moment by the chopper, achieving a total control over the energy we want to store.

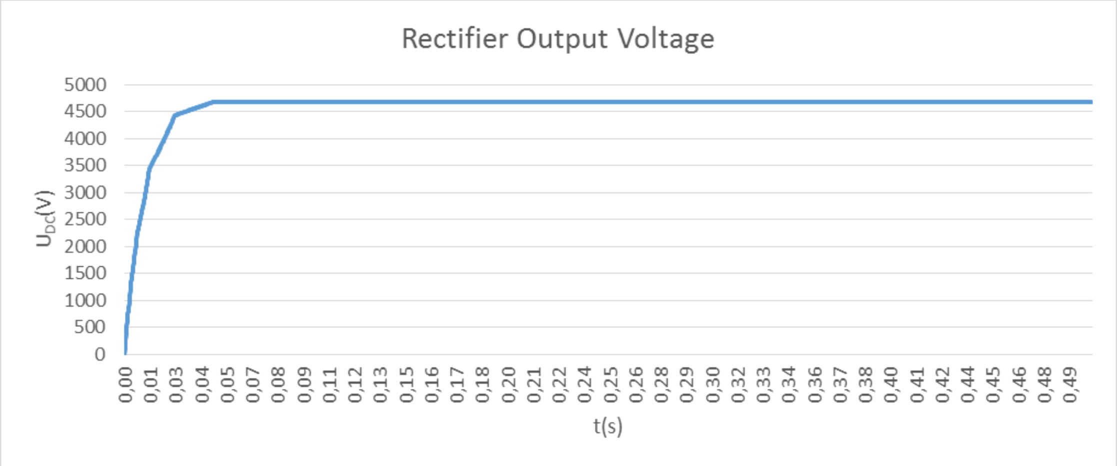

Figure 8. Voltage at the output of the rectifier. Source: Own elaboration.

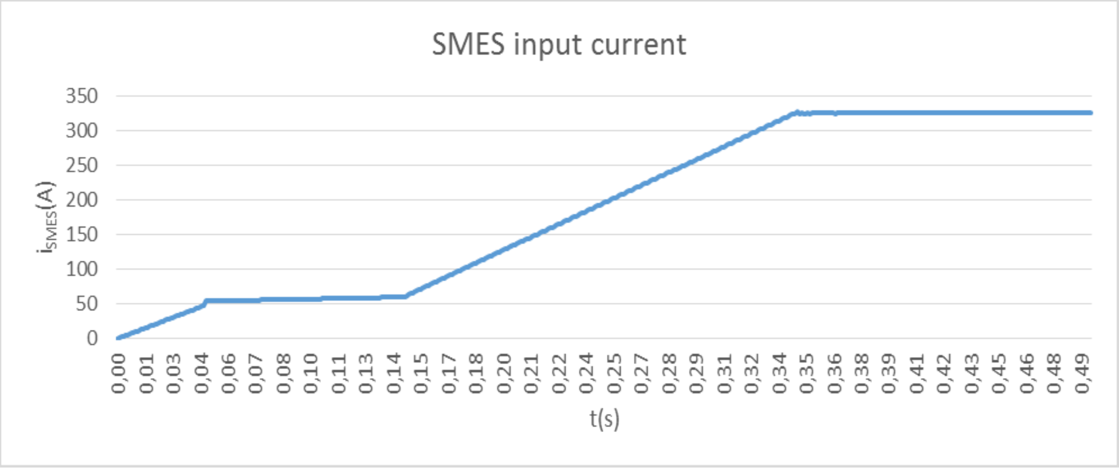

Figure 9. Current at the entrance of the SMES. Source: Own elaboration.

For a system connected to the network, a reliable and rapid response data acquisition system allows the increase of the efficiency and accuracy of the measurements, and therefore in the system operation.

4.2. Discharge of the Storage System

Once the system is charged, we can discharge the energy stored in the coil. This energy is provided by means of the control of the current, with the chopper and the converter in inverter mode. Then, by means of the control system, a rapid drop in the coil current i_{SMES} (t) is imparted, as shown in Figure 10. This setting is reflected in the voltage in the capacitor of the converter, noticing the change from the reached values to 0 V, Figure 11.

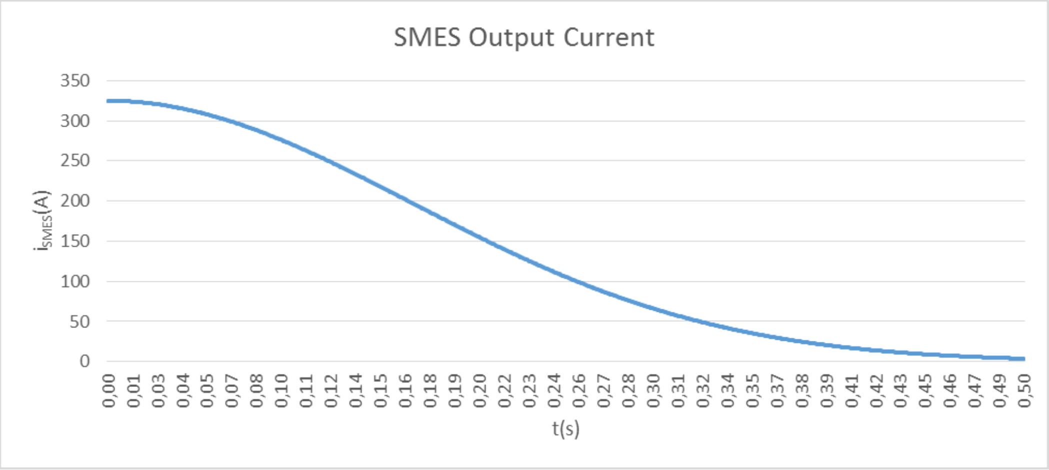

Figure 10. SMES output current during discharge. Source: Own elaboration.

Furthermore, the inverter provides a sinus signal, at 50 Hz and an effective voltage of 2000 V, which, after going through the filter, is refined to remove the undesired harmonics hat are introduced by the electronic elements of the circuit. In order to obtain the three sinusoidal phases, the signal inversion is carried out by means of the IGBT's continuous voltage switching with weighted sinusoidal pulse width (SPWM) [26]. The inverters with this kind of setting are easy to filter because the coupled harmonics are distant from the main harmonic.

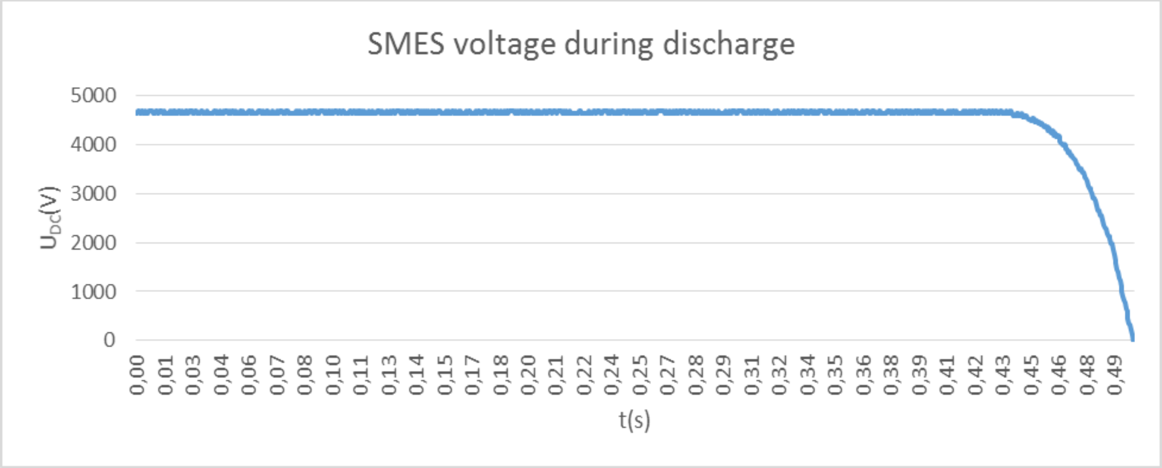

Figure 11. Voltage in the capacitor during discharge. Source: Own elaboration.

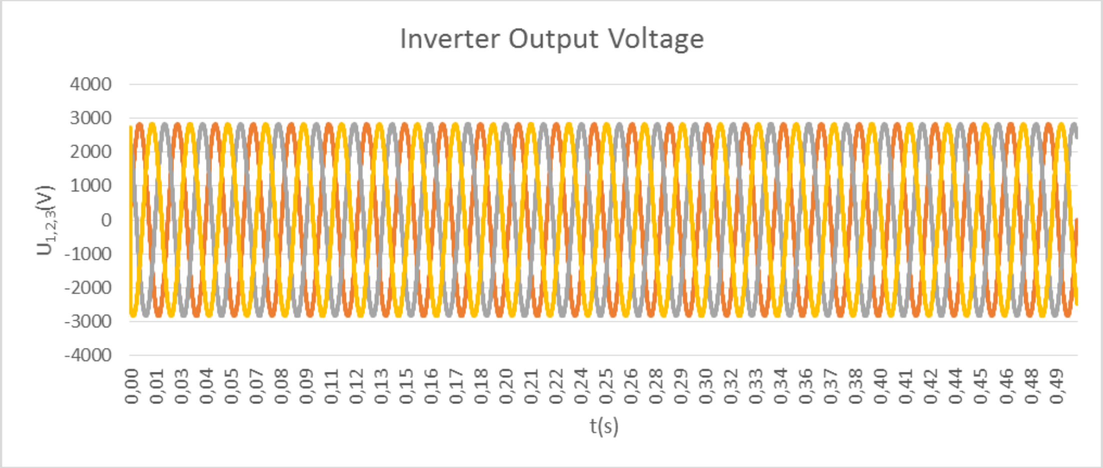

Figure 12. Phase voltage at the inverter output during discharge. Source: Own elaboration.

An important characteristic has to be emphasized, obtained from the simulations of this type of ESS. Because of the short distance between the storage systems and loads, small network losses occur. These losses are only shown in the loads that are connected to the ESS.

5. Discussion

It is necessary to take into account the characteristics of the electricity network, such as the large number of generation sources, the length of the transmission and distribution grid, as well as the wide variety of loads in the electricity network.

In the case of the smart city, the SMES system has been positioned in the distribution grid, in medium voltage, to support the loads related to industrial production. This implies that the distance between the storage systems and the loads is not large, so the resistive and capacitive effects are not relevant in this study.

With the simulations, you can see the limitations that these types of systems have on the electricity grid. The main technical limitation is the short discharge time of these systems, owing to their high power density. On the contrary, this provides great advantages, such as the possibility of being used for the compensation of energy fluctuations. However, at present, they cannot be considered as a long-lasting auxiliary energy support system.

Although it is true that these ESS allow control of the fluctuations of the network, largely caused by the connection of loads, there are elements or configurations that allow to control that connection of loads. Among the most used are three-phase star-triangle motor connection, connection by means of a soft starter or frequency converter connection.

However, the "Reglamento Electrotécnico de Baja Tensión" (REBT), electric normative manual Spanish, in Instruction ITC-BT-47, requires the incorporation of suitable systems that limit the intensity at the engine start [27], or another loads, that greatly introduce distortions to the network. Despite the use of these devices or configurations, signals that can influence the quality of the network signal are always introduced.

As discussed at the outset, one must take into account the interrelation between the different blocks that interact in the smart cities. In the case of the electrical network, it is important to highlight the communications system in the electricity system. The main objective of the communication systems in the smart grids is to strengthen and automate the network, improve its operation, the quality indexes and reduce the losses during operation.

Increased storage capacity in SMES systems and the adequacy of the energy conversion rate are the most important factors in the applications of this ESS in intelligent electric grids. In terms of configuration, it should focus on DFACTS models, distributed AC distribution systems with the aim of solving the quality problems of power. On the other hand, there are technical limitations that prevent its use being generalized in storage systems. Until technical solutions and technologies are developed to solve this problem, a hybrid systems called HESS can be used as a solution. Compared to SMES high power density systems, hybridization focuses on combining them with other high energy density systems, the most important factors in the applications of these systems in smart electric grids:

- Batteries-SMES: Hybrid models with SMES and batteries is the most used, owing to the wide variety of battery types. The simulation of this type of systems has been carried out and a suitable mathematical model has been obtained [28, 29].
- CAES-SMES: This type of system has not been used because of its high complexity and cost. In spite of this, this hybridization is compatible because of the technical characteristics of each of the systems.
- Fuel Cells-SMES: This type of system has been tested and simulated with the aim of creating a small-scale efficient storage system for use in electric cars [30].
- PHS-SMES: PHS systems are the most widespread storage systems and are oriented towards large capacity systems. This type of systems should be utilized for power supply in HV.

Table 1 shows different types of ESS with their associated characteristics. Here you can see the storage capacity and operation of different ESS and the possibility of hybridizing the systems:

Table 1. Summary of the characteristics of the hybrid architectures [31].

Technologies	Capacity (MWh)	Power (MW)	Response time	Discharge time	Maturity	Life time (Years)	Efficiency (%)
Battery: Lead–acid	0.25~50	≤100	millisecond	≤4h	Demo~Commercial	≤20	≤85
Battery: Lithium-ion	0.25~25	≤100		≤1h	Demo	≤15	≤90
Battery: NaS	≤300	≤50		≤6h	Commercial	≤15	≤80
Battery: Vanadium Redox	≤250	≤50	≤10 min	≤8h	Demo	≤10	≤80
FES	≤10	≤20	≤10 min	≤1h	Demo~Mature	≤20	≤85
PHS	5000~14000	500~1400	sec~min	6h~24h	Mature	≤70	≤85
CAES	250~2700	50~135	≤15 min	5h~20h	Demo~Commercial	≤40	≤85
DLC	0.1~0.5	≤1	≤10 ms	≤1min	Commercial	≤40	≤95

SMES	1~3	≤10	≤10 ms	≤1min	Commercial	≤40	≤95
Thermal	≤350	≤50	≤10 min	N/A	Mature	≤30	≤90

As for the architecture model to be used, hybrid systems can be grouped into 3 main types:

- Active Parallel. This model consists of connecting each ESS with an independent adaptation system to converge in another one and to be able to adapt the signals in a single one that meets the conditions to be supplied to the electric network, Figure 13.

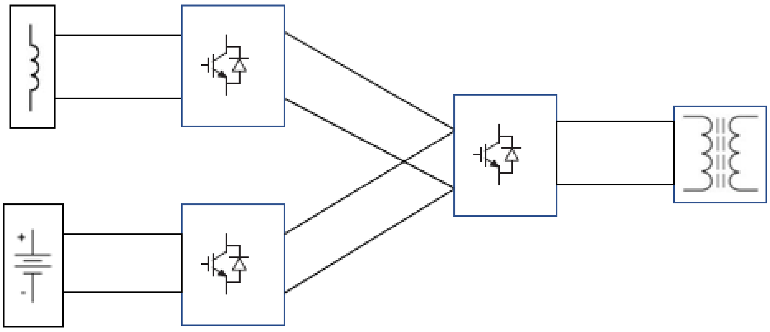

Figure 13. Active Parallel model adapted from [28].

- Passive (or direct) parallel. This model consists of the direct connection with a single adaptation system, without other intermediaries, Figure 14.

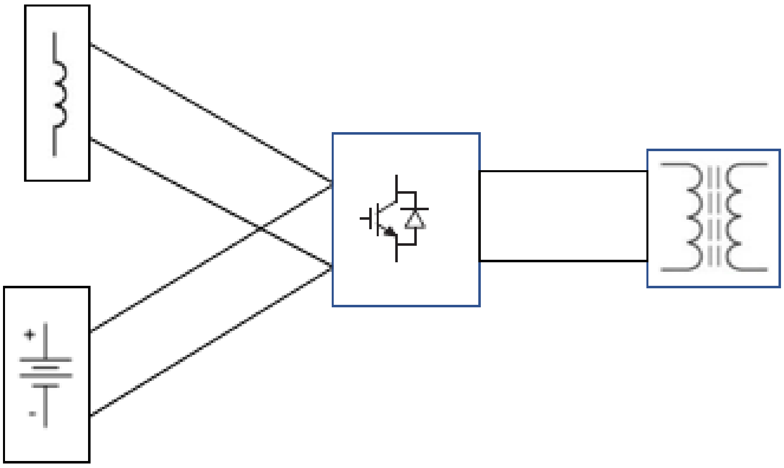

Figure 14. Passive Parallel model adapted from [28].

- Cascade: Finally, the cascade model consists of linking the ESSs with their corresponding adaptation system (Figure 15).

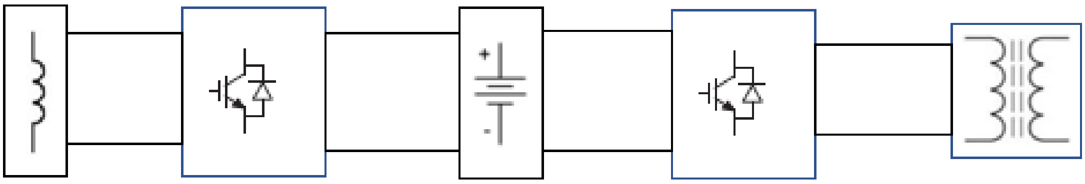

Figure 15. Waterfall model adapted from [28].

Table 2 shows a summary of the characteristics of the different architectures discussed [28].

Table 2. Summary of the characteristics of the hybrid architectures [28].

	Active parallel	**Passive parallel**	**Cascade**
Scalability	Scalability is higher because the number of power conversion steps between any ESS and load is always two, and the power conversion loss does not increase as the heterogeneity increases	Limitation provided by a single adaptation system	Scalability in these systems is limited to the operation
Flexibility	A variety of control and energy management strategies can be implemented	There is no flexibility in the selection of ESSs nominal voltage	Lack of freedom in the control policy
Operation	Each ESS can operate at its specific voltage, which allows the specific power and specific energy be optimized using the best available technology	Simplicity but the current distribution between ESSs is uncontrolled and determined just by the factors which vary with voltage	Provides decoupling of the ESSs which allows active energy management by use of additional power conditioning between ESSs in turn
Cost	More expensive	Less expensive	Expensive
Others	The stability is also improved since a failure of one source still allows the operation of the other	Easy implementation	The cascade architecture is restricted in terms of scalability because it suffers from more conversion losses as the number of power conversion steps increases

These hybrid architectures are controlled by the central control system of each ESS that communicates with the communications equipment of the central control system of the facility, being able to send status and alarm signals, and receive commands. On the other hand, has four outputs for contactor control or equivalent protection elements of the ESS.

In the case of Smartcity Málaga, the distributed storage system must be attached to the generator elements mainly, with the dual mission of storing energy and regulating the energy generated by wind or photovoltaic systems.

As for hybrid storage systems, they should be considered in industrial environments or environments in which the load requires a considerable instantaneous power input that high energy density systems cannot handle. Figure 16 shows the distribution of the generator systems of Smartcity Málaga [10].

Figure 16. Distributed Generation in Smartcity Málaga. Source: [10].

Each storage module must have monitoring equipment that communicates, via standard RS-485, with the central control system of the ESS. This monitoring includes temperature, voltage, current and load status, plus other multilevel alarms.

In this case, the control equipment of the storage system must be formed by an automaton equipped with different modules. The communications of the PLC signals can be made by the conventional telephone data communication network, using TCP/IP protocols, by a wireless telephony backup system, in case the telephone connection by cable fails, or by Power Line Communications (PLC), using power cabling as a support for communications.

6. Conclusions

We designed and simulated a storage system SMES that can be adapted to the Spanish electricity network. Knowing the proper functioning of these storage systems allow their inclusion in the Spanish electric system. Through simulation, we have seen the behaviour of the systems and the advantages they can bring to such complex systems as Smart Cities.

Electric energy storage systems with high power density can be used to eliminate signal fluctuations and support industries starting with elements such as three-phase induction motors, which can introduce harmonics and signals that impact the quality of the signal. The current peak for the electric motor start-up may contribute imbalances in the electric network indirectly affecting other connected loads. For that reason, Smart cities may contribute a big advantage in industrial areas where the use of high-density power ESS, such as batteries or other systems, do not add that start-up power peak needed for these kind of loads. We have to keep in mind the characteristics of the smart cities themselves. The electric and energetic system of this concept is based on energy saving and increasing the efficiency in its generation, transport, supply, and use.

Despite technical advantages that the SMES systems provided by the Spanish electric network, there are several negative points that impede the implementation and development in electric systems. Along with the high cost of construction and operation, compared with other ESS with similar characteristics such as superconductors, there is a need to form hybrid systems together with high-density power ESS.

SMES, by themselves, have little future, as long as the technical characteristics do not improve, such as rising the energy density or adding a system that allows working with a continuous supply regimen. This implies the need to develop hybrid configurations that can overcome these disadvantage.

Appendix A

In order to obtain the maximum energy of the SMES system, it must be taken into account that it consists of a coil of a determined material with an indicated geometric shape. For this, the storage energy of a coil is given by the inductance and the current.

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

After the transformer, the next circuit block is the star-connected LCL filter, Figure A.1. LCL filters are specially designed to eliminate the harmonics of the current absorbed by 6-pulse power converters. They are essentially passive filters based on a series-parallel combination of inductors and capacitors, adapted to filter the input of the power converters.

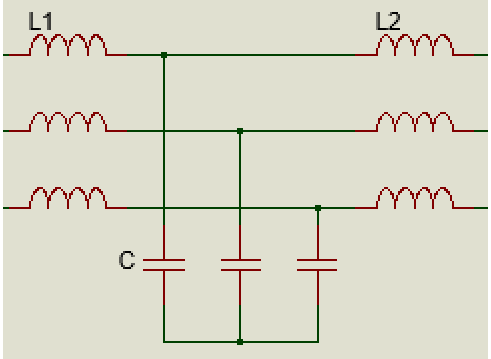

Figure A.1. LCL filter circuit adapted from [15].

The LCL passive filters have a high quality factor, therefore, they show a low damping to the resonance frequency that can cause instability in the system. One way to increase damping is by adding a resistor in series with the capacitor. It should be noted that selecting a very large R-resistor will greatly reduce the oscillation at the resonance frequency as well as the efficiency of the system. With all this, and neglecting the value of the resistance, we obtain a transfer function [32]:

$$\frac{I_2}{V_a}(s) = \frac{1}{sL_1L_2C(s^2 + \omega_{res}^2)} \tag{2}$$

In which:

$$\omega_{res} = \sqrt{\frac{L_1 + L_2}{L_1L_2C}} \tag{3}$$

It should be noted that the value of the capacitor C is limited to the maximum consumption of the reactive power allowed by the inverter:

$$Z_C = \frac{V_0}{I_c} \tag{4}$$

In which:

$$C = \frac{1}{\omega \cdot Z_C} \tag{5}$$

With ω is the frequency of the grid in rad/s.

The resonance frequency of the LCL filter should be located between 10 times the grid frequency and half the switching frequency, in order to avoid resonance problems in the low and high part of the harmonic spectrum [33].

$$10 \cdot \omega \leq \omega_{res} \leq \frac{\omega_{con}}{2} \tag{6}$$

It is also necessary to take into account parameters that can influence the quality of the signal. Among others, Total Harmonic Distortion (THD) is found.

$$THD = \frac{1}{V_{01}} \cdot \sqrt{\sum_{n=2,3,..}^{\infty} V_{0n}^2} \tag{7}$$

The THD indicates the total harmonic content, but does not indicate the level of each of the components. The aim is to reduce THD to values close to 8%, as required by IEC-61000-3.4 [34] and IEEE-519.

Following the circuit block is a three-phase converter, as shown in Figure A.2. The purpose of this converter is twofold, on the one hand, it converts the alternating signal into a continuous one when it is attempted to charge the storage system and on the other hand converts the direct current of the charged coil into alternating current to supply to the grid. This block can work in a controlled or uncontrolled way through the control system of the IGBTs, with the goal of gaining wave quality.

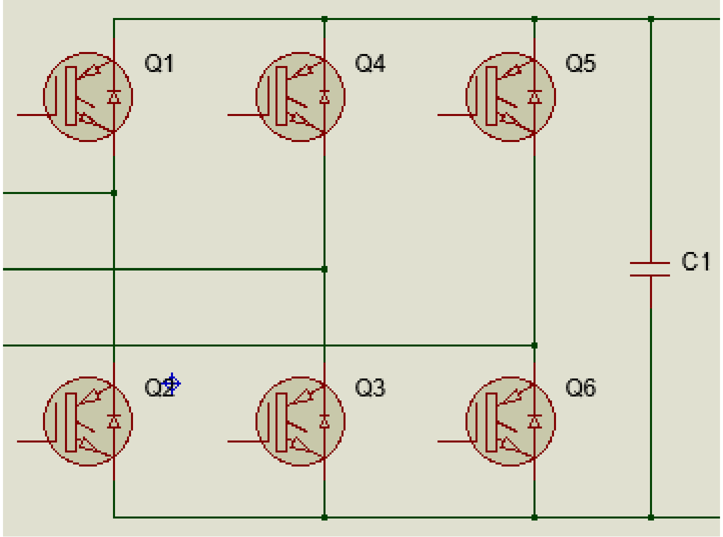

Figure A.2. Converter circuit. Source: Adapted from [15].

This circuit consists of a bridge of 6 IGBT power transistors with parallel protection diodes. A capacitor is then used to stabilize the charge voltage. To obtain the characteristic capacity of the capacitor, the input power of the inverter must be taken into account, as shown in equation (8).

$$C = \frac{P_n}{2 \cdot \omega \cdot v_0 \cdot \Delta v_0} \tag{8}$$

In which:

v_0 is the mean voltage in the capacitor, and

Δv_0 is the ripple of the voltage allowed in the capacitor (1%).

This converter circuit works in 3 modes. The first, in charge mode, the converter operates as a rectifier, in this case the chopper uses the control strategy of a current cycle. When the current reaches the nominal value, the SMES system will be switched in persistent mode to keep its current at a constant value, thus storing the energy. In the third mode, the discharge mode, the chopper uses the control strategy of a voltage cycle, the converter functions as an inverter to transfer the stored energy from the coil to the grid.

It is therefore essential to use a chopper circuit, which is shown in Figure A.3, for the proper functions of a DC-DC converter to regulate the input to the coil or its output.

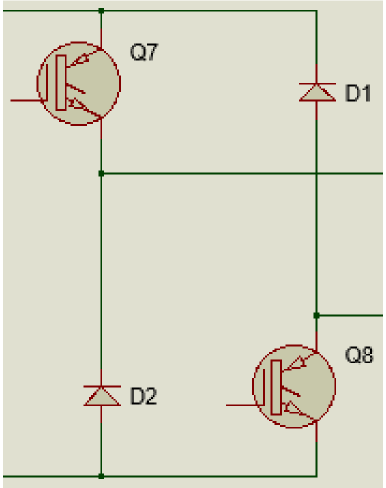

Figure A.3. Chopper circuit. Source: Adapted from [15].

Finally, there is the SMES system. This system is represented in the circuit as a coil but it must be borne in mind that behind the coil is a cryogenization system that allows the coil conductive element to be cooled to a temperature below the critical temperature at all times, it depends on that the system does not have losses in the storage part and, therefore, its efficiency.

As indicated above, it must be borne in mind that the inductance of the coil depends on its geometry and the material used. This influences the charging and discharging times of the coil, an essential issue for the design of a complete SMES system, together with the auxiliary electrical system, as it is one of the disadvantages of these systems.

$$i(t) = \frac{u_{dc}}{R_{eq}}(1 - e^{\frac{-R_{eq}t}{L}}) \quad (9)$$

In which:

u_{dc} is the voltage behind the rectifier, and

R_{eq} is the equivalent resistance seen from the coil.

Appendix B

The storage of electric energy in the smart city, both at low voltage (LV) and medium voltage (MV) levels, is considered a distributed resource. The capacity to store electrical energy, as well as the DG, allows to improve the grid quality and reduce imbalances in the demand curve. Also, the ESS allow to satisfy the demand when there is a temporary wear between the tip of consumption and the point of generation.

It should be borne in mind that SMES systems in particular have a number of strengths, of which the following [35-42] include:

- Short response time: The response time of these systems is mainly limited by the data acquisition system, both the grid and the ESS system, as well as the electronic control system. Nevertheless, this ESS stands out for a considerably low response time compared to other systems.
- High performance: It has a high performance of energy transformation. Mainly, the losses are concentrated in the electronic conversion system.
- High power density: This is one of the main characteristics that make its use remarkable for industrial zones within the smart cities.
- Wide range of uses: There are many uses in which it can bring a differential value with respect to other ESS. Possible uses include charge monitoring, power reserve, emergency elements, Uninterruptible Power Supply (UPS), adaptation of voltage levels and frequency regulation or as protection elements.

- High charge/discharge cycles: This extends the life of these devices and is due to the absence of mechanical elements that tend to wear out more than the electrical elements.
- Specialized work: The construction of this type of systems enables the creation of high-skilled jobs during the operating time, emphasizing that this period is usually very high.

Apart from the large number of advantages shown, there are some drawbacks that currently prevent SMES systems from being more widespread. Among them we can highlight:

- High manufacturing costs: This is the main drawback of this type of systems. These high costs come mainly from the manufacture of coil cryogenization systems.
- Low Energy Density: These systems can bring a lot of energy in a short amount of time. This can be a disadvantage when it is intended to have continuous power auxiliary systems.
- Possible health risks for the magnetic fields generated: Although there are no studies that certify or completely reject this statement, it is a subject that can provoke social rejection, in the same style as a nuclear power plant.

In Figure B.1 an example schema can be observed with the location of the storage systems in the smart grids, taking into account the main function dematerialized by them in the system. It is also possible to observe the differentiation by voltage levels according to the segment of the grid:

- Transport grid: HV and MV
- Distribution grid: MV and LV

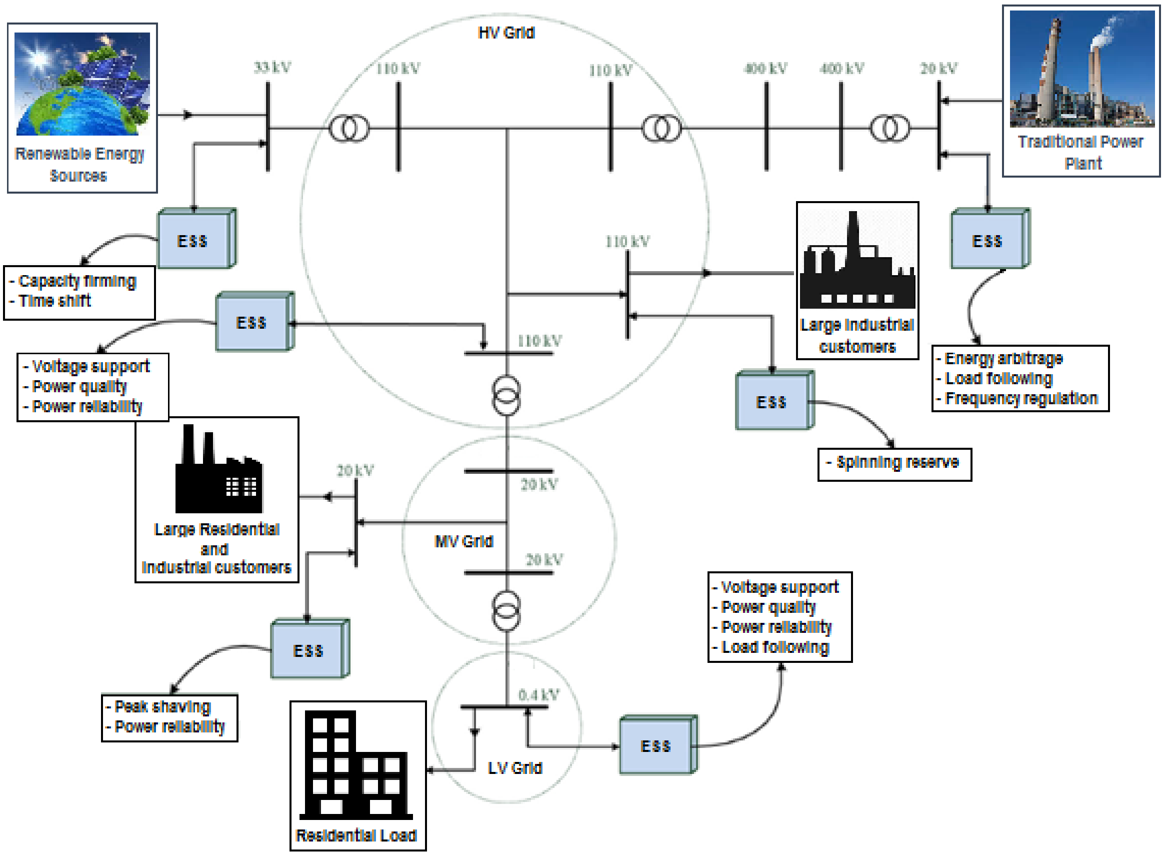

Figure B.1. Location of ESS in the electricity grid. Source: Adapted from [36].

In the concept of smart city, the storage system has control devices, adaptation and coupling to the grid. Among the main devices that make up these systems are:

- Storage system: Composed by the SMES system and the cooling system.
- Charge/Discharge management system: Element that provides the state of charge of the SMES system.
- Adaptation system: Adapt the signal between the distribution grid and the storage system.

- System of control: Element in charge of administering the system, in consideration of the different slogans.

This system can be summarized by a block diagram in Figure B.2, where all these devices are schematically shown.

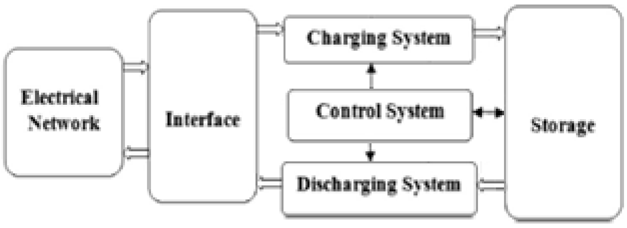

Figure B.2. Schematic of the storage system. Source: [43].

This scheme can be converted into the circuit of symbols shown in Figure 4, where the devices discussed above are specified. It is a system oriented to the simulation so these blocks are translated in the filter LCL, the converter, the Chopper and the system of storage SMES, represented with a coil and to which it is associated the whole system of refrigeration. For a real system, soft-start elements or system protection elements, such as disconnectors, should be taken into account.

One of the most important elements of grid-connected storage systems are the parallel monitoring and control systems capable of adapting to the signals and with the ability to act for the correct operation of the whole system. Some of these control signals are:

- Voltage and current at the input and output of the filter.
- Voltage U_{DC} in the capacitor C_2, after the output of the inverter.
- Current at the input/output to the SMES system.

Apart from the variables indicated, as well as the control elements of the inverter and the Chopper, the cooling control of the SMES system must be taken into account. This implies the need to have the temperature of the building material of the coil below its critical temperature. The critical temperature Tc depends on the material to be used, LTS (*NbTi*) and HTS (*YBCO*, *BSCCO*) [44]. This cooling system is usually linked to the global control system, discussed above.

This control system can be summarized in Figure B.3, although it may vary depending on the configuration in blocks (D-SMES), its application or if it is part of some type of hybrid storage system [28]. These systems must also monitor the quality of the signal in the grid, so that the load voltage for proper operation is taken into account.

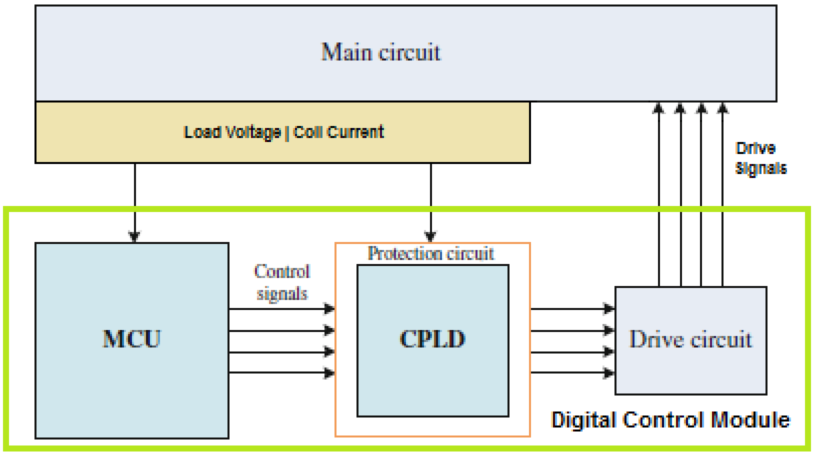

Figure B.3. Control module of an SMES system adapted from [45].

Considering the instantaneous load and the quality of the electric current, the monitoring and operation system must send the different setpoints for activating the IGBT switches, S1-S8, with a certain activation sequence. You must also keep track of the ESS charge level, in case the charging or charging operation is viable at any given time, or if it is necessary to keep the stored energy in Stand-by.

Regardless of the devices that are used, you must take into account the currents and operating voltages for the correct choice of these devices. One of the problems that can be found is the overheating of the semiconductors, in particular the IGBT's and the diodes. Despite being power elements and designed for large currents, they are the main elements that can cause losses in operation, so choosing a suitable device and a suitable working current and voltage can reduce these losses considerably or even failures in the system [46]. This is why the design of liquid cooling systems, which considerably reduce the losses caused by energy dissipation in semiconductors, [47-50].

On the other hand, Figure B.4 shows a basic operation flowchart for controlling the charging or charging of the SMES system.

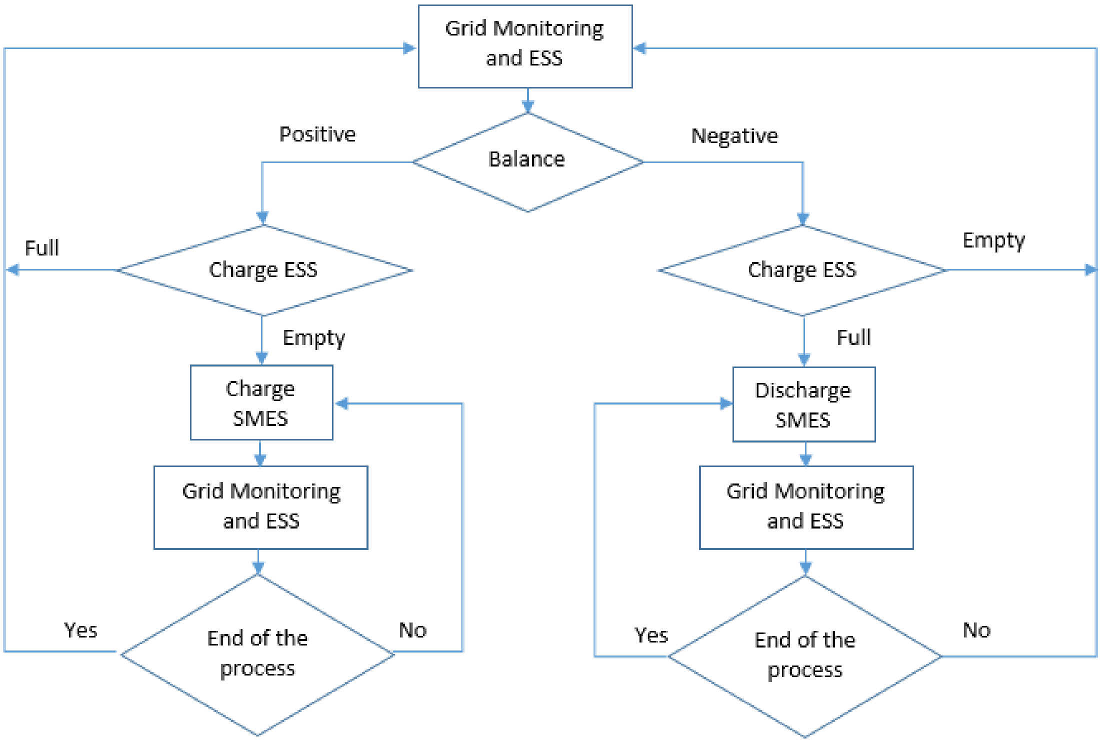

Figure B.4. Control diagram of a SMES system. Source: Own elaboration.

Appendix C

The project Smartcity Malaga was launched in 2008 by Endesa [10], a company that seeks to focus on this and other similar projects in concepts such as:

- Improved grid operation.
- Improving efficiency.
- The incorporation of renewable energies through distributed generation.

It is necessary to have as reference that the storage system used for the project Smart-city Malaga is based on a rechargeable lithium-ion battery system. The total set of batteries installed consists of 60 modules, of 1,766 kWh per module, reaching a total storage of 106 kWh.

In addition, Endesa has participated in R&D projects such as DENISE [51] or STORE [52], obtaining very interesting theoretical results that Smartcity Málaga has collected and demonstrated on a real scale in the city of Malaga, mobilizing a very important amount of means.

The Smartcity Malaga project grid consists of three distinct areas [10]. At the top level is the MPLS grid. At a second level, there is the so-called distribution grid (from the communications point of view) that connects the control centres (located in Seville) and the Operations Management Centre with the main HV substations. It consists of a main ring that is divided into two segments, according to the transmission technology used, namely:

1. Tour in the interior of the province of Malaga. Direct connection to optical fibre using native IP technology (Gigabit Ethernet). Bandwidth available 1 Gbit/s.
2. Connections to Seville, which are carried out transporting the IP over SDH technology. Bandwidth available 50 Mbit/s.

The links used for ring redundancy and give capillarity to the grid are connections at 2 Mbit/s and 64 kbit/s, depending on the existing transmission technologies. For this fiber optic grid a Gigabit Ethernet ring has been built that allows the integration of all the services in a safe, flexible and efficient way. Finally, there is the access grid, composed of the transformation centres that communicate with one or more HV substations.

References

1. Red Eléctrica de España, REE. http://www.ree.es/es/red21/redes-inteligentes/que-son-las-smartgrid# (Accessed on 22/05/2018)
2. Red Española de Ciudades Inteligentes, RECI. http://www.redciudadesinteligentes.es (Accessed on 22/05/2018)
3. SMART CITIES. Documento de visión a 2030 (2015), Grupo Interplataformas de Ciudades Inteligentes, GICI.
4. Los antecedentes y el estado de arte de la Generación Distribuida en España. SUELOSOLAR. http://www.suelosolar.com/newsolares/newsol.asp?id=7091 (Accessed on 22/05/2018)
5. Colmenar-Santos A, Rosales-Asensio E, Borge-Diez D, Blanes-Peiró J. District heating and cogeneration in the EU-28: Current situation, potential and proposed energy strategy for its generalization. Renewable and Sustainable Energy Reviews 2016; 62: 621-639.
6. 7º Congreso Aula Greencities, 2012. Las comunidades energéticas y la generación distribuida. http://aulagreencities.coamalaga.es/las-comunidades-energeticas-y-la-generacion-distribuida/ (Accessed on 22/0852018)
7. Colmenar-Santos A, Molina-Ibañez E, Rosales-Asensio E, Blanes-Peiró J. Legislative and economic aspects for the inclusion of energy reserve by a superconducting magnetic energy storage: Application to the case of the Spanish electrical system. Renewable and Sustainable Energy Reviews 2018; 82: 2455-2470.
8. Centros de Transformación MT/BT. Schneider Electric. http://umh2223.edu.umh.es/wp-content/uploads/sites/188/2013/02/04-II-Master-Cuaderno-Tecnico-PT-004-Centros-de-Transformacion-MT-BT.pdf (Accessed on 22/05/2018)
9. Ren L, Tang Y, Shi J, Dou J, Zhou S, Jin T. Techno-economic evaluation of hybrid energy storage technologies for a solar–wind generation system. Physica C 2013; 484: 272–275.
10. Endesa. Smartcity Malaga: A model of sustainable energy management for cities of the future. https://www.endesa.com/content/dam/enel-es/endesa-en/home/prensa/publicaciones/otraspublicaciones/documentos/SMARTCITY%20MALAGA.%20A%20MODEL%20OF%20SUSTAINABLE%20ENERGY%20MANAGEMENT%20FOR%20CITIES%20....pdf (Accessed on 22/05/2018)
11. Ciudades Inteligentes. Hoja de Ruta (2012), Observatorio Tecnológico de la Energía (OBTEN) – IDEA.
12. Borge-Diez D, Colmenar-Santos A, Perez-Molina C, Castro-Gil M. Experimental validation of a fully solar-driven triple-state absorption system in small residential buidings. Energy and Buildings 2012; 55: 227-237.
13. Global EV Outlook 2015, IEA, Paris. https://www.iea.org/ (Accessed on 22/05/2018)
14. Global Energy Storage Database, Sandia National Laboratories. http://www.energystorageexchange.org/ (Accessed on 22/05/2018)
15. Zhu J, Qiu M, Wei B, Hongjie Z, Lai X, Yuan W. Design, dynamic simulation and construction of a hybrid HTS SMES (high-temperature superconducting magnetic energy storage systems) for Chinese power grid. Energy 2013; 51: 184-192.
16. Saboori H, Hemmati R, Jirdehi MA. Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems. Energy 2015; 93: 2299-2312.
17. Ould-Amrouche S, Rekioua D, Rekioua T, Bacha S. Overview of energy storage in renewable energy systems. International Journal of Hydrogen Energy 2016; 45: 20914–20927.
18. Jin JX, Chen XY. Study on the SMES Application Solutions for Smart Grid. Physics Procedia 2012; 36: 902 – 907.

19. Aly MM, Abdel-Akher M, Said SM, Senjyu T. A developed control strategy for mitigating wind power generation transients using superconducting magnetic energy storage with reactive power support. Electrical Power and Energy Systems 2016; 83: 485–494.
20. Farhadi-Kangarlu M, Alizadeh-Pahlavani MR. Cascaded multilevel converter based superconducting magnetic energy storage system for frequency control. Energy 2014; 70: 504-513.
21. Zhu J et al. Experimental demonstration and application planning of high temperature superconducting energy storage system for renewable power grids. Applied Energy 2015; 137: 692–698.
22. Hasan NS, Hasan MY, Majid MS, Rahman HA. Review of storage schemes for wind energy systems. Renewable and Sustainable Energy Reviews 2013; 21: 237–247.
23. Dargahi V, Sadigh AK, Pahlavani MRA, Shoulaie A. DC (direct current) voltage source reduction in stacked multicell converter based energy systems. Energy 2012; 46: 649-663.
24. Tan X, Li Q, Wang H. Advances and trends of energy storage technology in Microgrid. Electrical Power and Energy Systems 2013; 44: 179–191.
25. Mariam L, Basu M, Conlon, MF. Microgrid: Architecture, policy and future trends. Renewable and Sustainable Energy Reviews 2016; 64: 477–489.
26. Bose BK. Modern power electronics and AC drives. Prentice Hall PTR (2002). http://een.iust.ac.ir/profs/Arabkhabouri/Electrical%20Drives/Books/Bimal%20K.%20Bose-Modern%20power%20electronics%20and%20AC%20drives%20%20-Prentice%20Hall%20PTR%20(2002).pdf (Accessed on 22/05/2018)
27. Reglamento Electrotécnico de Baja Tensión, 2015. http://www.construccionescasaalba.es/blog/instalacion_electrica/rebt-reglamento-electrotecnico-de-baja-tension/ (Accessed on 22/05/2018)
28. Hemmati R, Saboori H. Emergence of hybrid energy storage systems in renewable energy and transport applications – A review. Renewable and Sustainable Energy Reviews 2016; 65: 11–23.
29. Li J, Gee A M, Zhang M, Yuan W. Analysis of battery lifetime extension in a SMES-battery hybrid energy storage system using a novel battery lifetime model. Energy 2015; 86: 175-185.
30. Louie H, Strunz K. Superconducting Magnetic Energy Storage (SMES) for energy cache control in modular distributed hydrogen-electric energy systems. IEEE Trans Appl Supercond 2007; 17: 2361–4.
31. Palizban O, Kauhaniemi K. Energy storage systems in modern grids—matrix of technologies and applications. J Energy Storage 2016;6:248–59.
32. Nieves-Portana M. Diseño de filtros de acoplamiento para convertidores en fuente de tensión: Aplicaciones en la calidad de onda. Universidad de Sevilla, Escuela Técnica Superior de Ingeniería, Departamento de Ingeniería Eléctrica (2010). http://bibing.us.es/proyectos/abreproy/70304/fichero/PFM_MANUEL_NIEVES_PORTANA.pdf (Accessed on 22/05/2018)
33. Liserre M, Blaabjerg F, Hansen S. Design and Control of an LCL- lter-based three-phase Active Rectifier. Industry Applications, IEEE Transactions 2005; 5, 1281-1291.
34. IEC, International Electrotechnical Commision. http://www.iec.ch/ (Accessed on 22/05/2018)
35. Aneke M, Wang M. Energy storage technologies and real life applications – A state of the art review. Applied Energy 2016; 179: 350–377.
36. Palizban O, Kauhaniemi K. Energy storage systems in modern grids – Matrix of technologies and applications. Journal of Energy Storage 2016; 6: 248–259.
37. Kousksou T, Bruel P, Jamil A, El Rhafiki T, Zeraouli Y. Energy storage: Applications and challenges. Solar Energy Materials & Solar Cells 2014; 120: 59–80.
38. Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy 2015; 137: 511–536.
39. Zheng M, Meinrenken CJ, Lackner KS. Smart households: Dispatch strategies and economic analysis of distributed energy storage for residential peak shaving. Applied Energy 2015; 147: 246–257.
40. Chatzivasileiadi A, Ampatzi E, Knight I. Characteristics of electrical energy storage technologies and their applications in buildings. Renewable and Sustainable Energy Reviews 2013; 25: 814–830.
41. Ferreira HL, Garde R, Fulli G, Kling W, Lopes JP. Characterisation of electrical energy storage technologies. Energy 2013; 53: 288-298.
42. Colmenar-Santos A, Linares-Mena AR, Velazquez JF, Borge-Diez D. Energy-efficient three-phase bidirectional converter for grid-connected storage applications. Energy Conversion and Management 2016; 127: 599–611.
43. Akinyele DO, Rayudu RK. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments 2014; 8: 74–91.

44. Hirano N, Watanabe T, Nagaya S. Development of cooling technologies for SMES. Cryogenics 2016; 80: 210–214.
45. Hossain J, Mahmud A. Large scale renewable power generation: Advances in technologies for generation, transmission and storage. Springer Science & Business Media, 2014.
46. Datasheet IGBT: FD400R33KF2C-K. http://www.mouser.com/ds/2/196/Infineon-FD400R33KF2C_K-DS-v02_02-en_cn-464697.pdf (Accessed on 22/05/2018)
47. Refrigeración líquida directa de módulos de potencia en convertidores para la industria eólica. http://www.convertronic.net/Control-termico/refrigeracion-liquida-directa-de-modulos-de-potencia-en-convertidores-para-la-industria-eolica.html (Accessed on 22/05/2018)
48. Kim SC. Thermal Performance of Motor and Inverter in an Integrated Starter Generator System for a Hybrid Electric Vehicle. Energies 2013;6(11):6102-6119.
49. Teodori E, Ponter P, Moita A, Georgoulas A, Marengo M, Moreira A. Sensible Heat Transfer during Droplet Cooling: Experimental and Numerical Analysis. Energies 2017;10(6):790.
50. Li J, Jiang Y, Yu S, Zhou F. Cooling Effect of Water Injection on a High-Temperature Supersonic Jet. Energies 2015;8(11):13194-13210.
51. DENISE. Inteligent, Secure and Efficient Energy Distribution. http://www.cedint.upm.es/en/project/denise (Accessed on 22/05/2018)
52. STORE. http://www.store-project.eu/ (Accessed on 22/05/2018)