Study of a supercapacitor solution as a replacement of an energy storing motor of 1500 kW at OKG 3 nuclear reactor

Master's Thesis

By

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Abstract

The reliable operation of nuclear reactors is contingent upon precise control mechanisms for critical components, such as the head circulation pumps. This master thesis investigates an innovative approach to address the ramp-down speed of these pumps during external electrical grid failures by exploring the application of a supercapacitor group. Presently, the existing solution relies on a fly-wheel motor to provide additional energy during speed reduction, but persistent maintenance issues, particularly related to sliding-bearing problems, have resulted in substantial costs.

This study employs a comprehensive research methodology that is based on a study of the energy and power needed, a preliminary sizing of the main components, and a simulation of the new system. The objective is to enhance reliability and reduce the maintenance costs associated with the head circulation pump speed control during periods of external electrical grid failures. This study serves as a base to analyze the feasibility of the project and possible weak points of taking this approach.

The findings of this research show that using a supercapacitor technology is a feasible solution that can fulfill all the security and performance standards expected in an application of this caliber and that from the operational maintenance point of view would imply considerable improvements due to its low maintenance work. The ability to seamlessly ramp down pump speed during external electrical grid failures is ensured and there are no noticeable security threats that could endanger the safety of the system.

This research not only presents a viable solution for the specific case of head circulation pump speed control during grid failures but also sets clear guidelines for important areas to consider when approaching the project. The outcomes give a green light to the realization of the project, which would be followed by a detailed technical analysis of every area of the project and the sizing of other little components.

Acknowledgments

Thanks to my family and friends for supporting me all the way here. Thanks to my supervisor from Lund University, Jörgen Svensson; and my supervisors from OKG, Anders Sehammar and Jonas Jönsson. This master's thesis would not have existed without your support during these last months.

Iván Arenas Kelbelova

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List of acronyms

AC	Alternate current
DC	Direct current
ES	Energy storage
ESF	Energy storage facility
EDLC	Electric Double Layer Capacitor
EOL	End of Life
ESM	Energy storage motor
ESS	Energy storage system
FESS	Flywheel energy storage system
HCP	Head circulation pump
LTO	Long term operation
NPP	Nuclear power plant
SC	Supercapacitor

1. Introduction

1.1. Background and motivation

Oskarshamn's nuclear power plant is located in the Simpervarp peninsula around 30 km north of the coastal city of Oskarshamn. It was formed by three boiling water nuclear reactors called Oskarshamn 1, 2 and 3; or as often are referred O1, O2 and O3 [25]. O1, the first reactor was inaugurated in 1972 and had a gross output of 495MW. O2 nuclear reactor was commissioned and connected to the grid soon after, being connected for the first time in October 1974. In the beginning it had a gross output of 590MW but after the power upgrade of 1982 it rose up to 630MW. At that time plans for the building of a third nuclear reactor of 1000MW gross output were already on progress. It wasn´t until March 1985 that this third nuclear reactor, O3, was first connected to the grid. After two power upgrades, the power reactor increased its maximum capacity, first up to 1200MW in 1989, and later up to 1450MW in 2011. Making it, as of today, one of the biggest nuclear reactors in total production globally and the biggest Nuclear Power Plant (NPP) in the Nordic countries.

During the first decade of the 2000´s new plans for modernization of both O1 and O2 were considered and partly developed with the goal of extending the lifespan of the reactors and maintaining secure operation of these. That was the idea until October 2015, when the decision for the premature shutdown of units 1 and 2 of the nuclear plant was taken. At this time, both are still under decommissioning and will be soon taken down.

O3 nuclear reactor is still under operation and is now preparing for entering long term operation (LTO), planning to extend the design lifetime of 40 years up to 60 years. What would mean operating until the year 2045. This extension in the lifespan comes with numerous maintenance projects necessary to ensure the security and correct operation of the reactor. On the other side, the interest in other projects that aim to improve the operation conditions or reduce operational costs regained interest. And from one of these the interest in this master thesis has emerged.

After the last modernization of the nuclear reactor O3, together with the project "Puls 2008", an energy storage system was introduced in the feeding system of the Head circulation pump (HCP) of the primary water circuit. Because of the reactor power upgrade, the need for a storage system to supply power arouse with the need of protecting the fuel against dry boil damage in case of an external grid failure. This energy storage system is formed by an energy storage motor (ESM), see Section 2.2; and an AC/DC converter that controls the velocity of the HCP motor through changes in the frequency on the AC side.

Under normal operation the ESM is turning under zero load, rotational kinetic energy is stored proportional to the inertia of the ESM. In case of a system failure the ESM would deliver the rotational energy stored and would feed the energy to the HCP motor. With the use of the frequency inverters the power coming from the ESM is delivered according to a predefined reference, which slows down gradually the speed of the HCP in about 8 seconds. This ramp down protocol prevents possible damages in the fuel due to dry boil and possible leakages.

The primary water circuit at O3 is fed by eight head circulation pumps (HCPs) and each one of these pumps has an energy storage facility (ESF) to ensure a correct ramp down on speed. Therefore, the energy storage system is present in eight places in the nuclear reactor. Additionally, the interest on this system could be present in other nuclear reactors with similar problems what could lead to further collaborations with OKG if the case is presented.

1.2. Problem statement and purpose

The problem that this master´s thesis attempts to solve is related with the energy storage solution given at the project "Puls 2008" named above. As it is mentioned in Section 1.1, the solution relies in an ESM as a main component. Since its commissioning this system has proved to have a relatively short lifetime and has presented complications in the bearing system, which has led to high maintenance costs.

The main cause is the continuous operation in zero load what leads to a phenomenon called Sliding bearing problem. The problem is caused by the bearings working at a high velocity with a low or zero momentum [27]. The consequence is that the bearing rollers start to partly slide instead of rotating. What leads to a reduced live time of the bearings. This phenomenon is well known in the train industry where some possible solutions have been explored, being most of them related to oil viscosity. Although some improvements could be made by modifying the viscosity parameters, the problem would still be present.

Together with the expected LTO the interest in finding a better solution for this system has appeared, expecting to avoid or reduce the actual high maintenance cost that the current system is causing.

This master´s thesis will serve as an evaluation of one of the plausible alternative solutions to this problem. Therefore, the goal of this thesis is to carry out a study of the possibility of replacing this ESMs by supercapacitor (SC) groups with the same function. Both the ESM and the inverter would be replaced by a DC-DC driver and a supercapacitor group forming a new ESF.

1.3. Thesis outline

The thesis report has been divided into 10 chapters; a general overview of the chapters is given it this section:

- **Chapter 1** serves as an introduction to the thesis. It describes the background, introduces the motivation of the project, sets the problem statement and states the purpose of the thesis.
- **Chapter 2** gives a theoretical background in particular technologies relevant later. It gives general insight on BWR reactors, giving a general description of the systems involved to give the reader a better understanding of where the system in question is located. It introduces the concept of ESM, the sliding bearing problem, and reviews some literature of other industries to see other applications where this technology is used. And finally, a review of supercapacitor technology is carried out. It specifies both physical phenomena, and an analysis of the state of the art of this technology.
- **Chapter 3** makes a general description of the systems that are most influenced by the project. The systems are introduced with the elements involved in each, the functions of each, and the interaction between them. Operation modes for the most relevant cases are also given.
- **Chapter 4** shows the calculation of the energy involved in the system. The energy available in the energy storage system right now, the actual minimum energy needed to perform the ramp down and the supercapacitor energy and sizing of it.
- **Chapter 5** evaluates a possible type-solution. It is not intended to be, neither a definitive, nor a deeply detailed description. It gives a general overview of a possible solution, possible components that could be used, and serves as basis to perform the simulations in the following chapter.
- **Chapter 6** models and simulate both the current system and exemple-solution proposed in the previous chapter. Most of the elements are taken from available electrical engineering libraries, while others have been modelled to fit more precisely the case of study.
- **Chapter 7** tries to give an economic analysis on different aspects of the new solution. It intends to serve as a base to understand which are the main sources of costs, critical resources in terms of economic cost and general overview of the project.

- **Chapter 8** analyzes all the information obtained through the thesis analyzing the value of the new solution. It includes technical aspects as well as economics and gives an overview of the simulations performed.
- Finally, conclusions and future work lines are stated in the last two chapters, **Chapter 9**, and **Chapter 10.**

2. Theoretical background

This master´s thesis is written assuming that the reader has a general foundation in electrical, energy and control engineering. So general equipment and phenomena related to these fields will not be explained and will be assumed known. Otherwise, there are some specific technologies that are of interest to this case which are convenient to describe and discuss beforehand. Either because they are especially relevant for this problem or because they have a special relevance for the next sections. An introduction to the software used for the simulation will also be made in this section.

2.1. Introduction to BWR reactors

There are two main typologies when referring to commercial nuclear reactors (NRs), pressurized water reactors (PWR) and boiling water reactors BWR. The three of the reactors present in OKG are of the BWR and thus it is of interest to give a general introduction to this type of technology.

BWR form part of the so-called light water reactors (LWR), and they use ordinary water as a carrier of the heat produced in the NR. On the power site different typologies can be found, but normally all are based on a natural cold source to perform the condensation.

In BWR the moderation and cooling of the NR is made by water. Together with the control rods, water limits the nuclear reaction and as mentioned, ensures adequate temperature in the core. The water circulation system that regulates the amount of water entering the core is the head circulation pump (HCP). And the electrical system that ensures the correct operation of the HCP is the system of interest for this project.

2.2. Energy storage motor (ESM)

The ESM is an electro-mechanical energy storage system. The physical principle behind technology is simple. The main elements of the ESM are an electric machine and a rotating mass (flywheel/rotor) fixed to its axis. To accumulate energy the rotational speed of the mass is accelerated, and the energy is stored in form of kinetic energy. To obtain the energy stored, the rotating mass is decelerated, and electrical energy is produced. The amount of energy stored (E) in the mass depends on the mass moment of inertia (I) of the mass and the rotational speed(w) at a given time instant.

$$E(t) = \frac{1}{2} I w(t)^2$$

Consequently, the maximum energy that can be stored in a given ESM depends on the maximum designed rotational speed, which is mainly limited by structural factors. The power delivered by this technology is again only limited by structural factors and depends on the maximum rotational acceleration/deceleration.

Normally an ESM is together with other components that form what is called a flywheel energy storage system (FESS). These components are the rotating mass (flywheel/rotor), the bearing system, an electrical machine, to convert electrical energy in mechanical and vice versa; and normally power electronics to adapt the variable frequency signal into a standard frequency signal, normally a combination of AC/DC and DC/AC systems.

Different options for each of the components mentioned can be found; a range of flywheels with different mass distributions, different technologies of electrical machines, multiple bearing alternatives and even multiple addons to increase the efficiency of the system. The bearing system, for this project, is of special importance. Due to the low load and high speed of the ESM, the bearings are being induced into slide movements that reduce their lifespan. This problem is further explained in Section 2.2.2.

2.2.1. State of the art

The ESM is a technology that has been used for centuries in different applications. Now, the interest in this technology is rising again since it seems to be a suitable solution for many different problems. Some of the most common industrial applications are enumerated below:

- Frequency regulation. The electrical frequency of an electrical grid is variable and determined by the multiple individual loads connected to it. In general, when the grid load is bigger than the grid power production the frequency of the grid decreases, and when the load is minor than the production the grid frequency increases. A deviation of this frequency from its nominal value has serious impacts on the lifetime of equipment connected to it, so it is important to maintain the grid frequency as close to its nominal value as possible. There are already compensation methods in place to take back the frequency to its desired value [20]. The basic characteristics of high life cycle and high power to mass ratio given by ESMs, make this technology a suitable and reliable solution for this task.
- Renewable grid integration. The intermittent availability of renewable technologies such as wind or solar power is the main limiting factor for these technologies. Different FESS solutions are being studied and tested to smooth the power delivery of these technologies.
- Automotive. Solutions for generative braking for urban vehicles applying FESS constitute the main interest in this field.

Other experimental applications are proving really good results in the locomotive, marine or aerospace industries. And the tendency points to a rise in this technology in the upcoming years. See [44][22][6].

2.2.2. Sliding bearing problem

The “Sliding bearing problem”, also referred as “skidding” in the literature, is a situation where a bearing that was designed to work under rotation conditions slides under a particular set of external loads. This phenomenon is often observed in high-speed low load applications, or when changes between low and high load are present.

This behavior leads to conditions that can noticeably shorten the life of the bearing. As it is explained in [29] “Whenever there is micro-sliding rather than rolling, there is superimposed frictional heating within the contact ellipse. This localized heating can degrade or break down the oil film, which leads to even more local friction and more local heat generation.”

Other applications where this problem is present is in train applications, the aerospace industry and it has even been observed in wind and gas turbines. In these applications this phenomenon has led to a shortening of the lifespan of the bearing compared to the expected lifetime. It appears that optimizing the lubricant and the lubrication process can diminish the occurrence of it, but there is not a definitive solution for this problem.

2.3. Pump curves

Pump characteristics are usually given in curves that allow the user to characterize the conditions of a given point of operation. These curves are normally represented with flow rate in the x-axis and pressure in the y-axis. A lot of information can be obtained from this type of curve, but for this project two basic concepts of these are introduced for later use. The head capacity curve or pump curve, and the system curve.

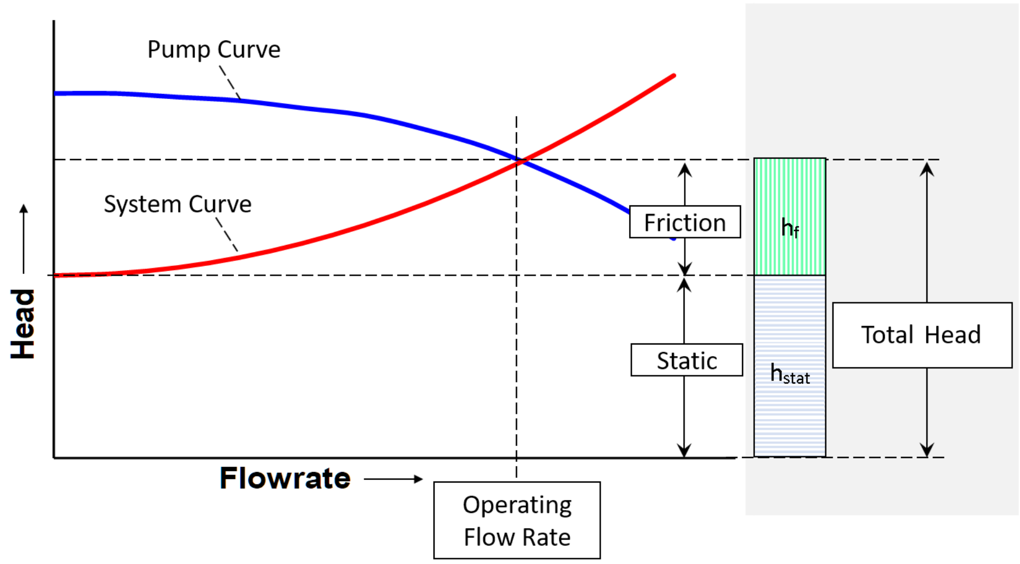

Figure 1. Pump and system curves scheme. Source [43].

- The pump curve for every % of the total power applied to the pump, there is a curve that relates the pressure that the pump is providing with the flowrate that goes through the pump. Generally, at higher flowrates the pump is able to provide less pressure differential.

- The system curve, on the other hand, represents the resistance that the system (conducts and static elements) presents to the flow. To higher the flowrate in the system the bigger the pressure drop is (resistance), that the system produces.

In every close cycle system, the point of operation is given by the intersection of these two curves.

2.4. Supercapacitor

In this chapter a better insight of the supercapacitor technology is given. Since it is a specific technology that may not be known by the potential reader, a general introduction is given first, followed by the different types of supercapacitors available and the phenomenon in which they rely, and by an introduction to sizing methodologies and relevant parameters; finally, a view of the state of the art is presented and general electrical models are introduced.

Supercapacitors can be considered an extension or a technological improvement of the conventional capacitor. In general terms the conventional capacitor stores energy by accumulating charges in the surfaces of two electrodes separated by a dielectric material. The basic equations that describe the behavior of a conventional capacitor are:

$$C = \frac{Q}{V}\ ; \quad C = \frac{\varepsilon_0 \varepsilon_r A}{D}; \quad E = \frac{1}{2} C V^2; \quad P_{max} = \frac{V^2}{4 * ESR}$$

Of which C is the capacitance, Q the positive charge, and V the voltage applied to the capacitor; ε_0 and ε_r the permittivity of free space and the permittivity of the dielectric material between electrodes, A the area of the surface area of each electrode, D the distance between them; E and P the energy stored and the maximum power in the capacitor given an external voltage; and ESR the equivalent series resistance of the capacitor.

The basic idea of supercapacitors is similar, with a focus on trying to maximize the surface areas of the electrodes and minimize the distance between them using special materials. This way higher energy storage capacities are achieved. At the same time, maintaining low values for the equivalent series resistance keeps high power densities close to the ones achieved by conventional capacitors.

When considering the whole picture of energy storage systems, supercapacitors occupy a region in between batteries and conventional capacitors in terms of the relation between energy storage capacity and power density. This is better represented in the Ragone plot, Figure 2.

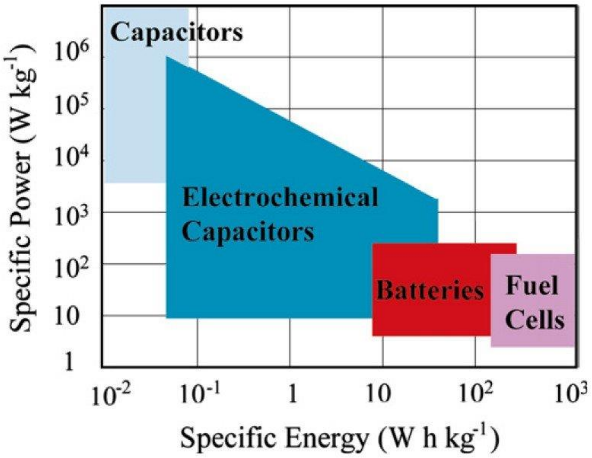

Figure 2. Ragone plot. Representation of the available technologies of ESS considering their relation Energy density/Power density. Source [30].

Observing the Ragone plot, Figure 2, electrochemical capacitors (also known as supercapacitors) are an intermediate solution between batteries and conventional capacitors in terms of the energy density and power density relation.

This relation is one of the main characteristics that make supercapacitors a suitable solution for this project. The high power provided, and the energy stored adapts adequately to the requirements of power of the HCP in case of a grid failure. Additionally, there are other characteristics that make this type of technology a good fit for this application. Supercapacitors, contrary to batteries, do not rely solely in chemical reactions to charge and discharge. These chemical reactions are never ideal and limit considerably the life and the performance of batteries. Relying only in electrostatic phenomena gives the advantage of having a much longer lifespan and a higher number of lifecycles. It is also a more robust technology and is not that dependent on temperature, so it is in general easier to handle.

It is interesting to compare in different features the different storage technologies to see how the ESM used now is similar, in term of characteristics, to other technologies available. This comparison can be seen in Figure 3.

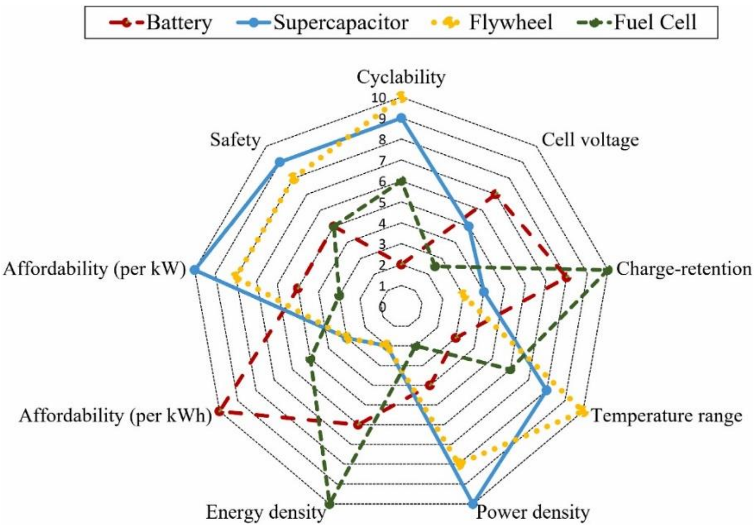

Figure 3. Energy storage technology relative scores in different features on a 0-10 basis. Source [15].

Although in an unconcise comparison, it can be clearly appreciated that the supercapacitor and the flywheel are similar in different aspects of performance. Both have a high-power density which is necessary for the case of this project. Both present good behavior regarding safety which is also relevant because of the field of application, and the cyclability is high, which translates into a long-life cycle.

2.4.1. Types of supercapacitors

The term of supercapacitor (SC) refers to the technology capable of storing energy using an electric field with two electrodes and one electrolyte. This description is broad and covers a wide range of technologies and materials that result in different characteristics on the final product. So first, it is important to make a review on the different technologies that lie within this description. Attending to the storage principle, three main types can be distinguished. [2]

- Double layer principle

The double layer principle is the accumulation of energy based on the accumulation of two types of charge in the surface of the electrodes. These charges are electrostatically stored at the electrode, and the density of storage is directly dependent on the voltage applied between them. This sequence includes an electrochemical behavior that consists in the adsorption and desorption of cations and anions in the electrodes.

- Pseudocapacitive principle

The storage of energy through pseudocapacitance is based on fast and reversible faradaic reactions, like those present on batteries. The main theoretical base of this principle is the relationship of charge acceptance and change of voltage, that result in similar characteristics to the ones in the double layer principle. Thanks to the electrochemical reactions, pseudocapacitive technologies present higher energy density than the SCs based in the double layer principle. With the drawback of sacrificing both, cyclability and power density.

- Faradaic principle

The Faradaic-based storage mechanism relays on redox reaction within the electrode. They present much higher energy density relative to the other alternatives, but since they rely in redox reactions this limits the power density and introduces irreversibility reactions that reduce its lifespan.

When selecting a supercapacitor solution for industrial application is relevant to have a classification of the technologies according to their characteristics, to evaluate their fit to the purpose of the application. This classification with some relevant characteristics can be found in Figure 4, and more detailed down below.

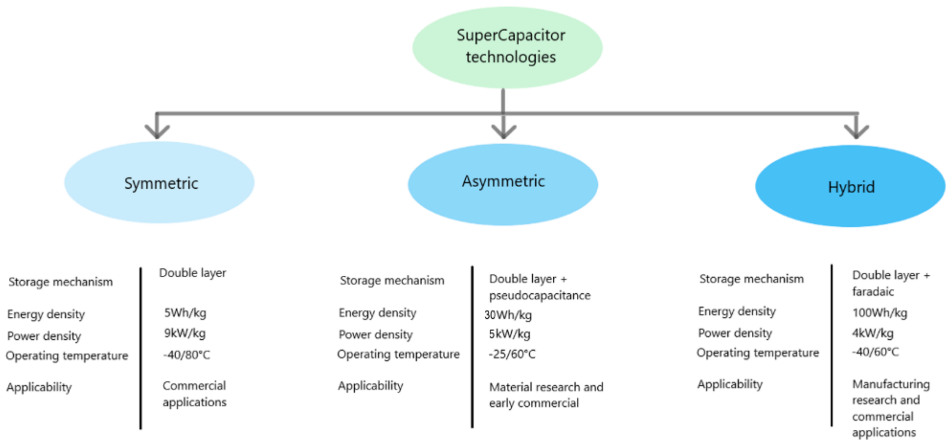

Figure 4. Supercapacitor technologies attending general characteristics. Based on table two of [2].

Figure 4 gives an insight of the three main groups of capacitors according to their general characteristics. As it is seen, mainly three groups can be distinguished: Symmetric, asymmetric and hybrid. Between them differences in the storage mechanisms, the rating values and the maturity of the solutions are presented. This is averaged data extracted from articles that review the available solutions in the market for this technologies [46][19][7][45]. This data should not be taken as exact values but as an indication of what to expect of each of them. A more detailed description of this is given down below:

- Symmetric SCs

The term symmetric SCs, also referred as EDLC, is used for those who use in both electrodes the same double layer material. Their energy storage mechanism is mostly based on the double layer principle. The use of different materials is being researched to improve the performance of this type of technology. Carbon nanotubes or graphene are the main areas of interest in the research field of this technology. Nonetheless, the technology is already in a high maturity state and commercially extended. Out of the three technologies it is characterized by a lower price, high efficiency and high cyclability, high power density (around $9kWkg^{-1}$) and relatively low energy density (around $5Whkg^{-1}$).

- Asymmetric SCs

The storage mechanism of this technology is based in double layer and pseudocapacitance effects. This technology aims to achieve both a high-power density and a high energy density, making use of both energy storage principles. They receive this name because two different capacitor-like materials are used to manufacture the electrodes. This type of technology can achieve relatively high energy density and power density (30 $Whkg^{-1}$ and $5kWkg^{-1}$), but the technology is not mature enough. The available solutions present high costs, shortened cyclability and low efficiencies [19].

- Hybrid SCs

In this case one capacitor like and one faradaic electrode are used. That way the energy density is considerably improved compared to Asymmetric or symmetric solutions (around $100Whkg^{-1}$). But the power density is compromised giving values around $4.5kWkg^{-1}$. The research on this technology is not as developed as the other two but there are already some industrial solutions available in the market.

The selection from these technologies is made according to the fit of these regarding energy and power requirements as well as other characteristics relevant in the industrial application of it: cyclability, safety, maintenance, or degree of maturity of the technology itself. The solution needs high power and relative low energy density, see Section 4. And at the same time be a commercially extended technology with a high life span. These characteristics are suitable for EDLCs (symmetric SCs); thus, this will be the option considered for the application.

2.4.2. SCs behavior

Due to the way SCs store energy, they present several behaviors that are not present or more present than in other ES solutions [2]. Thus, it is important to understand these behaviors and analyze if they could have some implications in the use of supercapacitors in this solution. After reviewing the literature, the two main behavior that should be particularly considered when designing a solution are:

- Electrical self-discharge.

Electrical self-discharge is defined as the effect by which an ES technology loses stored charge overtime. This is present in other ES technologies but is especially relevant for SCs, which has prevented its use in industrial applications for storages superior to 30 minutes.

In the case of this project the supercapacitor would be connected to the grid so it is expected that this would not affect the total charge of it, but how does it affect its efficiency? The main cause of electrical self-discharge is current leakage through the ion-conductive membrane. This could indeed happen either the SC is connected to constant supply or charged and disconnected. So, when selecting a particular solution, this phenomenon should be considered. Either by trying to find a particular solution that reduces this behavior or by adding these losses to the economic analysis.

- Temperature dependance

Temperature influences most of the ES solutions available in the market. In perspective, SCs are known to have a reasonable performance in extreme temperature conditions. Nonetheless, temperature is a factor that affects the capacitance of the SCs and thus should be considered during the design. Temperature increase causes a decrease in capacitance of about 0,1%C^{-1}[3], which under a difference of tens of degrees is a substantial effect. Data for the charge variation depending on temperature should be provided by the supplier and considered in the calculations, this is further explained in 2.4.3.

Temperature has also a noticeable effect on the lifetime of the equipment, this can be seen in Figure 5 where the dependance between operating life and operating temperature is analyzed for three different conditions.

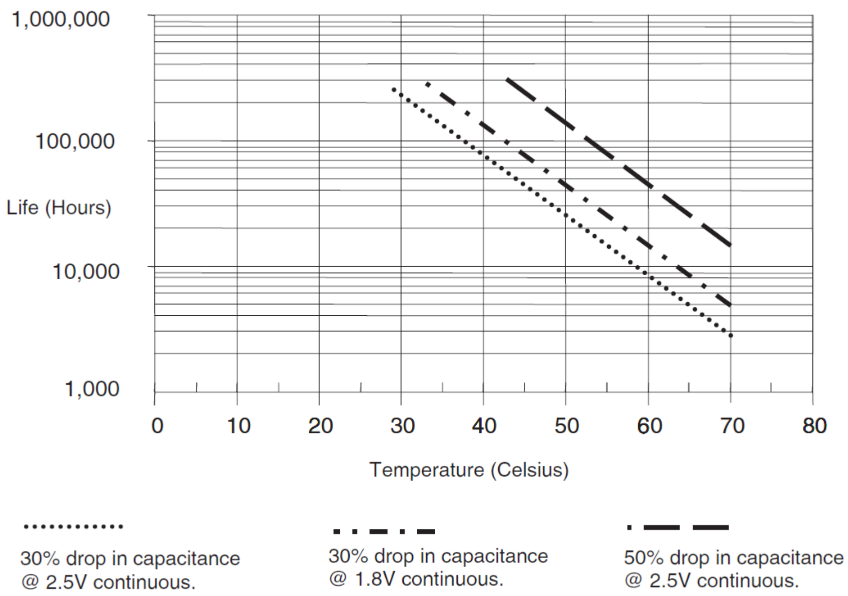

Figure 5. Operating life vs temperature and charge voltage. Source [8].

In the same technical note [8], an increase in 10 degrees in the ambient temperature affect the supercapacitor decreasing its lifetime by a factor of two. Considering both variations in capacity and in lifetime a dedicated ventilation system to maintain the ambient temperature in the desired range is recommended, as explained in the proposed solution, Section 5.3.4.

There are other effects that help to explain and predict how SCs behave under different conditions, among them: voltage dependence, charge distribution along the electrode, ohmic phenomena and high frequency behavior are the most relevant in literature. In the case of this project, losses or other effects derived by these phenomena will be included in the efficiency and final data provided by the supplier and do not have a particular interest for its analysis.

2.4.3. Supercapacitor Sizing

There are different ways to size a supercapacitor group according to the application and performance expected from it. In this section the basic concepts necessary for sizing of supercapacitor groups, a general sizing method and a power-based method are introduced [11][24].

Due to the type of the application this section will be focused on the sizing of EDLC type supercapacitors. A simplified equivalent model this type of supercapacitor is shown in Figure 6:

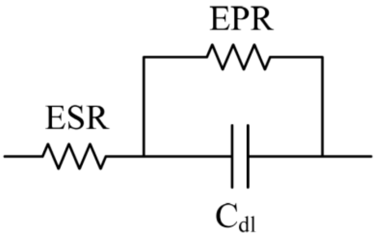

Figure 6. Simplified EDLC electric model. Source [11].

Figure 6 represents a simplified electric equivalent model of an EDLC. ESR is a serial resistance that models the Joule losses, EPR a parallel resistance which accounts for the self-discharge phenomenon and C_{dl} a capacitor that represents the actual capacitance of the EDLC.

An EDLC cell, as the one modeled in Figure 6, can be used alone in case of small applications, with low power and energy requirements. In applications for bigger systems such as this one, groups of capacitors are needed to achieve the desired specifications. Considering the simple model exposed before a way to calculate the equivalent resistance and capacity of the whole supercapacitor pack is given by the following expressions:

$$C_{pack} = C_{cel} \frac{number\ of\ cells\ in\ parallel}{number\ of\ cells\ in\ series}$$

$$R_{pack} = R_{cel} \frac{number\ of\ cells\ in\ series}{number\ of\ cells\ in\ parallel}$$

As described in [11] if a constant discharge current is assumed a 2-step algorithm can be followed to size the supercapacitor needed.

- Step 1. EDLC unit selection.

The first step is the selection of a commercial EDLC unit, obtaining the following technical properties from the cell, and setting the systems requirements:

- Maximum (V_{max}) and minimum (V_{min}) operation voltage during the charge-discharge cycles.
- Time constant of self-charge/discharge of the unit. It can be calculated as $\tau_P = EPR \cdot C$.
- Power P of the cell, using the assumption of constant power delivery $P = V_{max} \cdot I_{min} = V_{min} \cdot I_{max}$.
- Current value assuming again constant power delivery of the cell, $i = I_{av} = \frac{I_{max}+I_{min}}{2}$.
- The specific energy requirement of the application (Wh).

- Step 2. Cells needed of the selected supercapacitor unit.

In the second step, the number of cells in series necessary to obtain the maximum voltage is obtained to calculated.

$$number\ of\ cells\ in\ series = \frac{V_{max}}{V_{cell}}$$

And the number of parallel cells is iterated, from only one cell in parallel up until the capacitance of the specific application is reached or, a decision to go back and change the selected unique cell is taken.

This simplified method will converge to a given solution with the cell selected. None the less as it will be explained in Section 4.3, this method is too simplistic and does not fit the application adquately. Therefore, a second sizing method based in expected power is introduced, which will serve as a base for the sizing the supercapacitor specifically for the needs of this application.

The approach of this second method is thoroughly described in [24]. It starts by simplifying the EDLC model to the elements that are directly involved in power delivery, namely the capacitor and the resistance in series (R_{Csup} and $C_{sup.)}$. And defines basic variables that will later be used, this is shown in Figure 7.

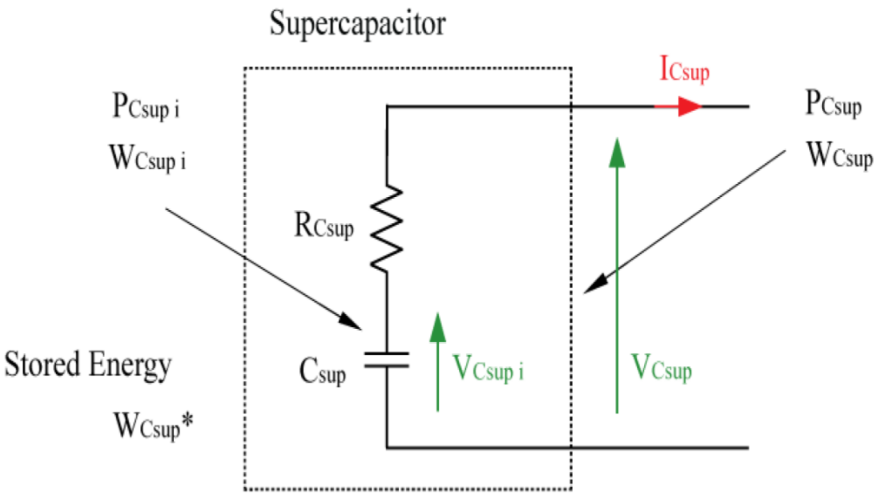

Figure 7. Model and parameter definition for power-based sizing method. Source [11].

The basic parameters of the model are R_{Csup} and C_{sup}. From these parameters the energy stored in the supercapacitor in a certain instant is $W_{C\_sup}{}^{*} = \frac{1}{2} \cdot C_{sup} V_{C\_supi}^{2}$. In case of having a low voltage allowable limit, meaning the lowest voltage that the system can operate in, the available power the energy available to use would be $W_{C\_sup}{}^{*} = \frac{1}{2} \cdot C_{sup} \cdot (V_{C\_supi\_max}^{2} - V_{C\_supi\_min}^{2})$.

Continuing with expression for no voltage low-limit, and observing that $V_{C\_supi} = V_{C\_sup} + R_{Csup} \cdot I_{Csup}$ and that $P_{C\_sup} = V_{C\_sup} \cdot I_{C\_sup}$, the energy stored in a certain instant $W_{C\_sup}{}^{*}$ can be expressed in terms of power and current:

$$W_{C\_sup}{}^{*} = \left(\frac{1}{2}\frac{C_{sup}}{I_{C\_sup}^{2}}\right) P_{C\_sup}^{2} + \left(R_{C\_sup} C_{sup}\right) P_{C\_sup} + \left(\frac{1}{2} R_{C\_sup}^{2} C_{sup} I_{C\_sup}^{2}\right)$$

The expression gives relevant information corelating the total energy stored, the power supplied, and the intensity provided. None of the two approaches are followed exactly to do the sizing of the SC group, since the required solution is more specific than the cases given here. Nonetheless certain steps and concepts are valuable and will be used.

Other important factors to consider when sizing supercapacitors is the derating factors and the utilization ratio. Derating factors estimate the deterioration of the main characteristics of the supercapacitor during their lifetime. The SC group is expected to achieve the required performance during the whole operation life. Applying derating factors to the main characteristics helps to ensure that. When sizing supercapacitors, the derating factors considered are Capacitance derating and ESR derating. Using the derating factors on the rated values gets the “End of Life” (EOL) value for the parameters. Both parameters should be found in the technical data of component provided by the manufacturer and have to be taken into account in the sizing. On the other side, the utilization ratio is a value that serves as a convenient way to express the amount of the total capacity that is being utilized. These parameters are explored further below.

- Capacitance derating

Article [42] explores the different aspects that influence the aging of supercapacitor. Among them, the most important are the operating temperature, the applied voltage, and the charge/discharge currents. The aim of the study is to show “the capacitance fade under different circumstances”. The information about capacitance derating must be given by the manufacturer. This one includes the degradation through the lifetime and the tolerances of the component. A typical value for capacitance derating in industrial solutions is 70%[23], considering that temperature, applied voltages and applied currents are within rated ranges.

- ESR derating

As with capacitance, aging considerably affects the value of the ESR, which is relevant for the sizing of the supercapacitor. This value should also be provided by the manufacturer for the selected component. A typical value for industry solutions is 200% of ESR derating [23], which means that the ESR expected at EOL is double as big as the rated one.

- Utilization factor

As it has been mentioned supercapacitors are not use to their full capacity in most applications. This has to do with the high currents necessary to draw the needed power for low capacitor voltages, which would lead to damage in the system. To avoid this situation a minimum operation voltage is introduced, and the charge and discharge of the supercapacitor is done within the rated voltage and this minimum voltage. The utilization factor helps to express the amount of energy that is being used from the total available energy, [23]. And is calculated in terms on the rated and minimum voltages in the following way:

$$\alpha_B = \frac{V_{max}^2 - V_{min}^2}{V_{max}^2}$$

Common values for this parameter are between 80-90%. This depends on the power demand over time and the characteristics of other components in the system.

Based on the terms introduced, a last sizing method is introduced that helps include these parameters in the sizing process. This one considers the parameters of utilization factor and the EOL parameters. This sizing methodology is an adaptation of the sizing methodology introduced in the article [23]. This is referred as “Supercapacitor Backup System Design Methodology”. It is based on the selection of a desired constant power output and a back-up time.

To obtain the capacity of the pack desired, given a backup time and a power output, the following expression is used:

$$C_{SC} \geq \frac{2 \cdot P_{BackUp} t_{BackUp}}{V_{max}^2 \cdot \left[\frac{\alpha_B + \sqrt{\alpha_B}}{2} - \frac{1-\alpha_B}{2} \cdot \ln\left(\frac{1+\sqrt{\alpha_B}}{\sqrt{1-\alpha_B}}\right)\right]}$$

And based on that capacitance, find a specific capacitor which pack resistance fulfills the following requirement.

$$R_{SC} \leq \frac{(1-\alpha_B) \cdot V_{max}}{4 \cdot P_{BackUp}}$$

The reason of the equivalence resistance requirements is set to achieve the peak power needed given the max voltage. To get more detailed information refer to [23] where the expressions are deduced.

2.4.4. Commercial development

The final solution selected is based on the options available commercially in the market. A short insight of the available supercapacitor cells and modules offered by the main manufacturers, is shown in Table 1.

Table 1. Basic characteristics of symmetric EDLCs offered by companies. Source [3]

Company	Device	C(F)	V_R (V)
Maxwell	Cell Module	1-3400 5.8-500	2.3-2.85 16-160
LS Mtron	Cell Module	100-3400 2.5-500	2.7-3 16-381
Nesscap Co.	Cell Module	3-5000 1.5-500	2.3-2.7 5-125
Panasonic Corp	Cell Module	2.2-100 0.1-1.5	2.3-2.7 3.6-5.5
Vinatech	Cell Module	1-3000 2.5-60	2.5-3 16-144
Ioxus Inc	Cell Module	400-3000 2.5-60	2.7 16-162
SPS Cap	Cell Module	1-5000 0.5-500	2.5-2.7 16-2300

Table 1 gives information about the different ranges of characteristics of EDLCs offered by different manufacturers. Except from Panasonic Corp, which only fabricates supercapacitors directed to the electronic industry, all the rest show similar characteristics. Unit cells of 1-3000/5000 F of capacity and operating voltages around 2.3-3 V. And modules of 1-500 F and 16-200 V, with some exceptions. This serves as a good reference for Section 4.3 to do the sizing before selecting an actual model.

2.4.5. Other industries

The SC technology is a mature technology and is already being used in different industries with positive results. The goal of this subsection is to study other uses in the industry and try to find some similarities with the expected application of this project.

As it has been explained during Section 2.4, the SC technology is characterized by having high power density and low energy density relative to the rest of ESS. In general, also presents high cyclability, good performance in extreme temperatures, and a less convenient high electrical discharge effect. Although these characteristics are poorly suitable with many ES applications nowadays (mainly mid/long-term storages), they are suitable for other applications that other technologies are unable to fulfill. The most common applications of this technology are in solutions that require high peak power requirements and high cyclability. Some of the industries that include this type of technology are:

- Energy industry

The transition to a more renewable based energy system opens the door for many static applications of SCs. Most of these applications are related with power fluctuations, which are characteristic of some of these renewable technologies. At the moment, the use of SCs in the pitch control of wind turbine is under growth being in 20-30% on these systems. Many studies about the use of SCs for corrections of high-dynamic issues present in Wind power turbines are also appearing. And its use in smoothing the power output of general renewable solutions is starting to arise.

Within grid management, SCs are widely used in electrical microgrids to deal with fast load fluctuations. This can be extrapolated to weak grids where its voltage stability can threaten the well-functioning of loads connected to them.

- Transport

Within the transport industry the use of SCs is widely spread for regenerative braking. This is mostly seen in trains and buses, which use SCs to store kinetic energy and reuse it when acceleration is needed, showing great efficiency performances. Applications in combination with batteries are arising for electric buses in cities. As well as applications of SCs in trolleybuses to cover short distances disconnected from the electrical grid, such as changes of lines or bus stops.

The applications within generative braking are also reaching the automotive sector, where passenger cars using supercapacitors for regenerative braking have appeared in the commercial market.

- Industrial sector

Within the industrial sector SCs are mainly found in machinery within different uses (agricultural, construction, mining, or harbors industries). Which is increasing even more together with the CO2 emission regulations. In general, the use of SCs together with batteries is increasing in combination with generative braking and recovering energy from discharging motions. In the case of mining, the use of these technologies is even more relevant since the emissions of other technologies in closed environments can have serious consequences for both, the health of the workers and the general safety of the facilities.

- Electronics

Many applications in minor electronics have been found for SCs, such as storage applications, power failure back-ups or real-time clock back-ups among others. Those are not of interest for this project, so no further details are given.

In conclusion, SC groups of medium and high size are commercially available and being used for many applications in different industries. Thus, is already a mature and industry-proven technology, which is highly important before considering it as a viable solution for this project.

2.5. Simulink

Simulink is a software developed by MathWorks, which serves as a graphical extension to MATLAB for modeling and simulation of systems [41]. Simulink in combination with the different pre-built libraries included in it simplifies the simulation of complex systems using generical models [40].

Simulink offers a great number of libraries of control and electrical systems. For this work mostly elements from the “Control system Toolbox”, “Simscape” and the base “Simulink” libraries are used.

- Controls system toolbox: “Control System Toolbox provides algorithms and apps for systematically analyzing, designing, and tuning linear control systems.” [38].

- Simscape: “Simscape enables you to rapidly create models of physical systems within the Simulink environment. With Simscape, you build physical component models based on physical connections that directly integrate with block diagrams and other modeling paradigms.” [39]

Most of the components necessary to model and simulate the system in Section 6 are available in these two libraries and the basic libraries of Simulink. More complex components not available as such in the libraries mentioned will be modelled from minor components, see Section 6.1.1.

3. System description

The purpose of this chapter is to give a detailed description of the systems directly involved in this project. The goal is to define the components involved, the functions of the systems, interactions between them and different operation modes, control routines and security measurements that are involved within them.

3.1. Primary water circuit

The primary water circuit is one of the alternatives to control and limit the nuclear reaction rate. Therefore, it serves for regulating the power output and start-stop protocols as well as a security interface to ramp down the reaction in case it is needed. The primary water circuit has a direct implication in the reaction rate inside the reactor. The higher the primary flux, the faster reaction rate in the system. Around 80% of the reaction in the core can be controlled by the primary flux.

In this section, a general description of it is given and the systems involved in its operation are introduced.

3.1.1. General scheme

The regulation of the primary water circuit involves multiple systems that are responsible for ensuring safe operation during normal circumstances and emergencies. In the scheme in the Figure 8 the main systems involved can be seen.

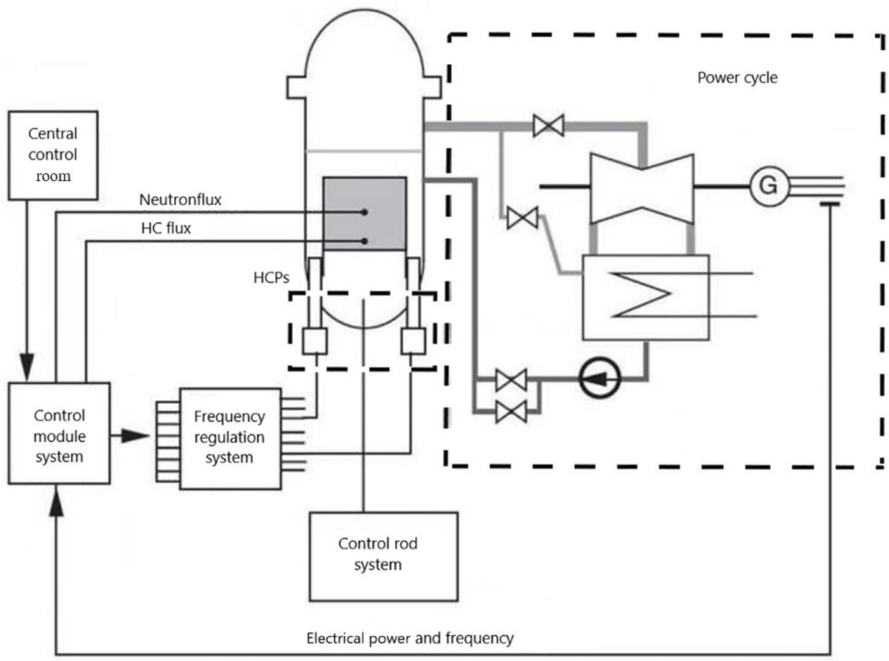

Figure 8. General scheme of the nuclear reactor with extra detail in the systems involved in the HCP control.

On the right side of the Figure 8 a simplified scheme of the power cycle is represented which include the turbine, generator, heat exchanger, a circulation pump, and valves. On the left side, the main systems that influence the HCP control can be seen with connections that represent the interactions between them.

As it can be seen, the main systems involved are the control module, which gives the setpoint condition for the operation of the frequency converters; the frequency modifiers, which are ensure that the HCP system follows the setpoint given by the control module; and the HCP system, which acts on the flux itself to control the nuclear reaction inside the core. Other systems influence in a minor way the primary flux operation, these are further explored in Section 3.1.2.

3.1.2. Systems description

The systems involved or related with the control of the primary water circuit are the following:

- Reaction rod system

The reaction rod system is in charge, together with the HCP system, of controlling the reactivity in the reactor core, in both, start-stop of the reactor, and normal operation. Regarding exceptional security situations, the rod system can be used to stop the reaction inside the core under critical conditions.

- Head circulation pump system

The HCP oversees cooling down the reactor core through the circulation of a water flux so dry-out conditions are avoided under any operation point. Under operation, it also actuates controlled by the frequency modifier system, to regulate the reaction inside the core through changes in the primary circulation flux. In case of an external grid failure, together with the ESM, will shortly maintain the HC flux during the ramp down of the HCP speed to ensure a safe slow-down of the flux.

- Frequency modifier system

The system has under normal operation the task of supplying the HCP motors with the necessary power, of variable voltage and frequency, to achieve the desired primary circulation flux. It needs to have the flexibility to vary the pump rotational speed from 41% to 100%. It will act as a limitation of the speed in certain abnormal situations and, during an external grid failure the system provides a gradual predefined down control of the speed of the pumps, so the integrity of the core is protected.

- Control module system

The control module system oversees the monitoring and control of the main head circulation flux to achieve the desired effect in the reaction inside the core. This is done via the frequency modifier, acting over the HCP motor speed, and with the actuators modifying the position of the control rods inside the core.

- Reactor security system

Each of the systems introduced has a vast amount of information explaining its functions, elements, control algorithm involved, security routines and operation under normal and exceptional situations between others. Describing all of them in such detail is out of the scope of this master thesis. This document will describe in more detail only the two systems that are most relevant to the topic treated in this master´s thesis. This is done in Section 3.2 and Section 3.3, where the system of the HCP and the frequency variation system are thoroughly described.

3.2. HCP system

The HCP system consists of 8 internal circulation pumps that lead the cooling water from the bottom of a tank to the top part of the reactor. Part of the cooling flux is led through the control rod joints. The 8 pumps are uniformly distributed so that the mixing between feed and circulating water is the same for every pump, keeping in that way an uniform entry temperature in the reactor core. The required pressure given by these pumps will be determined by the pressure losses in the primary circuit at nominal power and flow circulation. Each pump has connected its own heat exchange which evacuates the heat absorbed by the cooling flux.

The HCP motors connected to the pumps are wet asynchronous motors positioned vertically under the reactor tank. The HCP motors are fed via the frequency regulation system through the output transformer, this one adapts the voltage after the inverter to fit the voltage range needed by the HCP motor. The speed of these pumps is regulated through the variation of frequency and voltage supply by the invertors (given a manual setpoint or a setpoint given by the control module system). The speed of the pumps is measured by an inductive sensor located at the base of the HCP motor.

3.2.1. Control patterns

Changes in the nuclear reaction in the core can be made either with manipulation of the control rods or with the variation of the head circulation flux. Around 80 % of the reaction can be controlled with the help of the primary flux. The flux can be controlled in power control mode (electrical power or thermal power) or in speed control.

Electrical power control is used when a desired electrical power output in the reactor wants to be kept constant. In that way, changes in the plant efficiency or the fuel burn-out must be compensated by changes in the primary flux to compensate for its effects.

Thermal power control is used when a desired thermal reactor power wants to be kept constant. Fuel burn-out leads to regulations in the flux to keep the provided thermal power constant. During thermal power control the electrical output power is not consider and it could vary depending on the efficiency at the turbine plant although thermal power is kept constant. Normally this type of control is used from 3020 to 3900 MWt.

Speed control is normally used only at the start or stop of the power plant, as well as when the reactor is under a low reaction point. Under this type of control, the speed of the pumps is kept to a speed setpoint without considering the thermal or electrical power that may vary depending on other conditions. This operation mode is used in the case of external grid failure as will be explored below. With both speed and power control it is pursued to keep a flow of around 12000kg/s at a thermal power of 3900 MWt to obtain optimal fuel economy.

3.2.2. Operation

In this subsection the normal operation mode and the abnormal operation mode “failure of external grid” are described. Although many other situations are considered in the design on this system, the two mentioned are the most relevant for this thesis project. A reduction in the output power is achieved by reducing the pump speed. The control of the pumps under normal operation occurs from the control module system through variation in frequencies and voltages in the frequency regulation system.

- Normal operation

Under normal operation all the pumps are running with a circulation flux between 12000-14500 kg/s (1500-1812 kg/s per pump) depending on the actual operating requirements at that moment and producing a thermal power around 3900 MWt. It can be run either on power control or speed control depending on the external situation of the plant, although power control is more common under normal operation.

- Failure of external grid

After a failure in the external grid the first option for the plant main generator is trying a transition to in-house turbine operation. In this mode the reactor is operated in minimum velocity and all the electrical power produced is used only to keep the plant under operation. To achieve that mode a down control of the reaction must be performed with the regulation of the HCP to minimal velocity.

In case of a failure in the transition to in-house turbine operation there is no power feed that can keep the HC pumps running. In that situation the ESMs provide sufficient energy, using their inertia momentum, to maintain the primary flux long enough to ensure core cooling and avoid dry-out damage on the fuel. After that, the reactor is cooled by natural circulation.

3.3. Frequency converter system

The system has the main function to supply the HC pumps with power of changing voltage and frequency. There is one of these systems for each of the HCPs, so there is a total of eight frequency converter systems in the plant. The system has other functions besides the main function of providing the pumps with the necessary power supply. Between them:

- Under speed control a speed reference is given by the control module system and the system modifies the frequency and voltage to make the HCP follow the given reference.
- Acts limiting the speed in case of abnormal occurrences in the system; the system will dynamically adapt to up or down control the speed, keeping the neutron flux under acceptable ranges.
- Eliminate minor disturbances from the grid and give a suitable power feed to the HCP regardless of those.
- Provide a controlled ramp down of the HCP speed in case of an external grid failure. For that the support of the energy storage facility is needed.

3.3.1. Electrical scheme

To get a better understanding of the system a electrical scheme of it is shown in Figure 9.

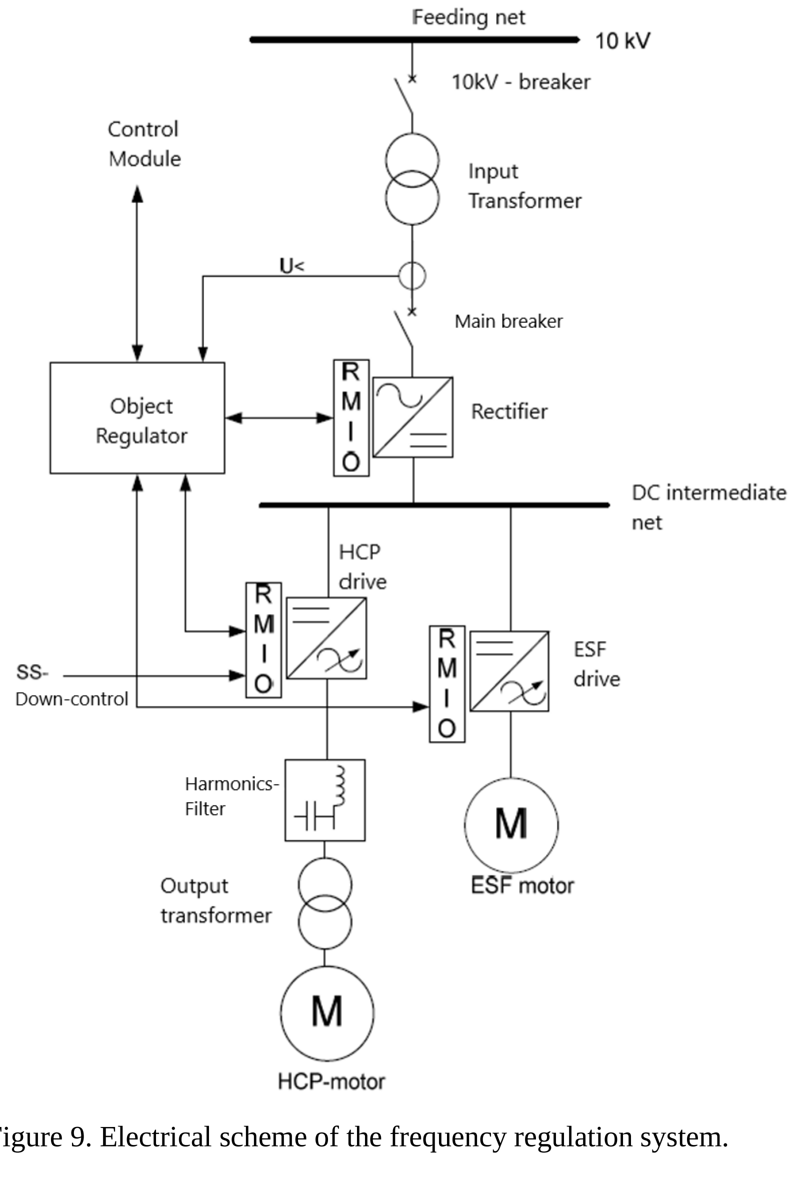

Figure 9. Electrical scheme of the frequency regulation system.

Figure 9 shows a simplified electrical scheme of the frequency regulation system, from its connection to the 10kV feed grid down to the connection to the HCP motor. The object regulator is represented with a black box representation together with the connections with the system.

As it is seen in the Figure 9, the voltage is transformed from 10kV at the feeding grid to 690 VAC, which is the nominal voltage for the drives. After the voltage is converted from AC to DC with help of a rectifier, at that point a intermediate DC interface with a voltage set by the grid appears. The DC voltage can be later transformed again to a variable DC voltage with the help of the drives.

In the system there are two drives, one which regulates the speed of the HCP motor and the other that regulates the speed of the ESMs. Before getting to the HCP motor the voltage from the drive is passed through a sinus-filter and an output transformer. The sinus-filter is used to eliminate harmonics before getting to the HCP motor. And the output transformer adjusts adequately the voltage coming from the drive to the nominal range of voltages of the HCP motor being the final voltage fed between 192-920V.

3.3.2. Physical description

The purpose of this section is to give more information about the elements of the system. A general description of the functions and relevant details and numbers are stated here. While the detailed technical data of the elements that will be later used for design and simulation purposes will be kept confidential due to company requirements.

- 10kV-breaker

The 10kV breaker unit consists of a circuit breaker, a relay unit, and a relay protection. The circuit breaker acts as overcurrent protection and ground current protection that triggers after a signal of the relay. The breaker can be operated from the control room.

- Input Transformer

The input transformer has as its main function the reduction of the voltage from the feeding grid 10kV to the nominal voltage of the rectifier 690V. The transformer is a dry-insulated, encapsulated transformer connected to the 10kV breaker unit in the primary side and the head breaker in the secondary side. To minimize disturbances on overhead grids, supply transformers in the same sub are designed with different switching types (Δ/Y and Y/Y).

- Head breaker, SACE-breaker

Before every frequency regulation system there is a head breaker. It is situated between the Input transformer and the rectifier. It is equipped with overcurrent protection and overload protection after the breaker there are grounding couplers so the system can be grounded temporarily under operation if its needed, normally for maintenance purposes.

- Rectifier

The rectifier is located just after the head breaker and is connected to the intermediate DC grid in which it sets the voltage level. It rectifies from a 3-phase 690VAC to 1000VDC. In the AC side there it is equipped with a low pass filter to filter harmonics. It feeds both the HCP and energy storage (ES) drives.

- Drive for HCP

The drive of the HCP converts the voltage from the DC voltage intermediate circuit into a three phase AC voltage cable. The drive has software that takes care of the regulation and protection. It regulates the voltage and frequency to keep the voltage-to-frequency ratio constant. Additionally in the same software there is an application which can handle a down control after the signaling of it or during a feed loss, which will make the HCP speed follow a predetermined setpoint (see Section 3.2.1).

- Sinusoidal filter

Apart from the filters included in the drive of the HCP, an extra sinusoidal filter is added after it to filter the harmonics down to the HCP.

- Output transformer

The output transformer is an autotransformer which has the function of transforming the voltage coming from the driver to suit the nominal voltage of the HCP. The nominal values of the transformer are 690/920V but due to variation in frequency and voltage from the power supplied by the drive, the voltage after the output transformer can range from 190 to 920V.

- Neutral-point equipment

The secondary side of the entry transformer is equipped with a neutral-point equipment that is able to detect ground faults that appear downstream of the transformer.

- Energy storage facility (ESF)

The energy storage facility is an asynchronous machine that is used to give a controlled slowdown of the HCP speed in case of a grid failure. At normal operation the ESF rotates with a rotational speed of 1800 rpm, and in case of a failure in the grid the rotational energy is converted back to electrical energy and the motor acts as a generator. And that makes the control down of the HCP possible, avoiding damage in the fuel.

- Drive for the ESM

Also referred to as ESF driver, it converts the DC voltage from the intermediate grid to a three phase AC voltage that feeds the ESF motor. By means of direct torque control it manipulates the frequency and voltage to control the ESM speed.

- Energy storage motor (ESM)

ESM feeds directly from the driver. At normal operation rotates without load, and in case of a grid failure it delivers the energy accumulated to assist the control down of the HCP in a predetermined manner.

- Control equipment

It consists of multiple control equipment linked with the drivers and sensors of the system. It is located in the control room and gives the possibility of manual control when it is needed.

- Object regulator

The object regulator consists of a Programmable automation controller together with I/O entries. Through it occurs the exchange of all the signals in and out the system. Under the case of grid failure, the object regulator sends the signal requesting the down control, but the setpoint to follow is given in a ramp down reference written in the HCP driver.

3.3.3. Control algorithms

Under normal operation the HCP drive receives a setpoint signal from the control module system, and adjusts the voltage and frequency fed to the HCP motor to follow the setpoint given. As it was explained in Section 3.2.1 this setpoint correspond normally either to power control or speed control. But regarding this system it is only seen as a setpoint.

Different types of abnormal operation are considered for the control of the system. For this project the case of interest is the “failure in external grid” case. Under that case this situation is signaled through the object regulator to the HCP motor drive, and after the signaling the drive starts to follow a speed ramp-down reference that is stored inside the software of the drive. This ramp reference is called “HCP down control ramp in case of undervoltage” and it can be seen in Figure 10. This ramp is used also for other situations as reactor shutdown notice or even under normal down controls in the plant.

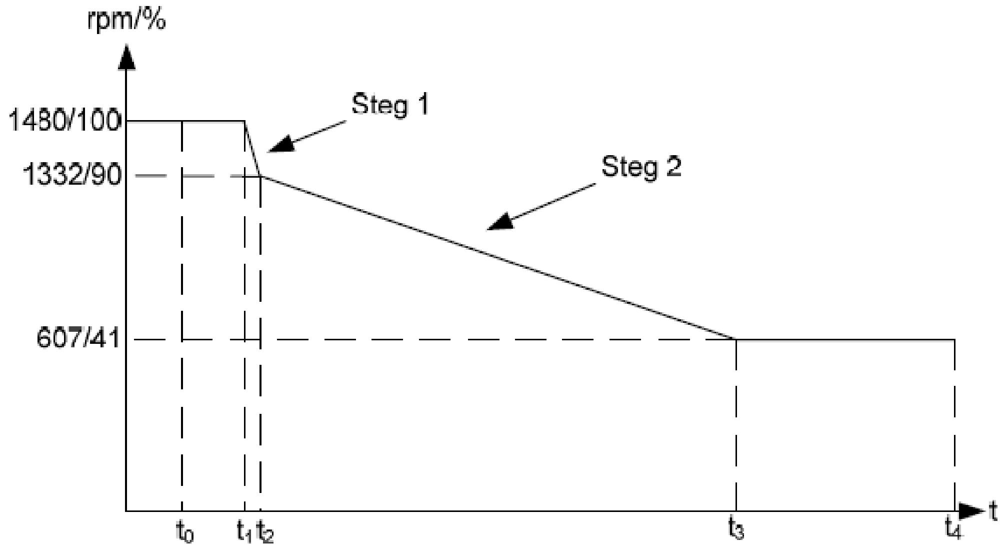

Figure 10. Ramp down speed reference for emergency stop protocols of the head circulation pumps.

The times given at the graph represent the limits on the different steps in the ramp down process. The graph and the limits mentioned are explained down below.

t0-t1	t= 0,25 s, “Flat-top”
t1-t2	t=0,13 s, Time for step 1
t2-t3	t= 5,5 s, Time for step 2
t3-t4	t= 2 s, The 8 pumps disconnect in sequence two by two with a time difference of 0,5 s.
t0-t4	t= 7,88s, Total time for the down control process

In case of a grid failure the HCP are controlled down according to the ramp at Figure 10. The ramp represents the time after the grid failure in the “x” axis and the rpm and rpm (%) referred to design values on the “y” axis.

The ramp down starts with a “Flat top” in which the speed of the pump is maintained during 0,55s in case the grid voltage has failed between a 25% and a 67%, or 0,25s in case the grid voltage has failed under 25% of the nominal value of the grid. In that way the system is resistant under short failures in the system, so in case a short failure (t<0,25s) do occur, it would not cause a control down of the HCP. The 0,55 s limit is set to fulfil the “Nordel-demand”, the Nordic Grid Code indications for this type of case.

After the flat top, the speed setpoint ramps down in two steps in a total of 5,63 s. At the end of the ramp down the reference has achieved its minimum speed and the disconnection of the HC pumps starts, disconnecting the pumps in pairs at intervals of 0,5s.

In the case that the grid voltage is recovered in the first interval, the pump recovers the feed from the grid and avoids starting the ramp down. In the case the ramp down has already started the down control would be first completed and the pump would maintain the rotation at a 41% of the nominal value without disconnecting.

3.3.4. Interactions

The frequency regulation system is the most relevant system for this thesis project. Therefore, it is relevant to review in detail the interactions that occur between this system and other systems around.

- Control module system

The frequency regulation system needs a velocity reference given by the control system to keep the HCP at the desired velocity. With the signal coming from the control module the drive will adjust accordingly the voltage and frequency fed into the HCP motor.

- HCP system

The frequency regulation system will deliver with the required power of variable voltage and frequency to achieve the adequate speed at the pump. The variation of the speed affects the flux speed, and the nuclear reaction can be thus controlled.

- Reactor protection system

The reactor protection system signals to the control system in case it is necessary to down control the system (via reactor shutdown signals). This type of signal occurs when a certain amount of undesired conditions are reached and signal to shutdown the reactor to ensure reactor safety. As it was mentioned in Section 3.3.3 these signals are handled in a similar way as an external grid failure. Given the signal from the reactor protection system, a ramp down like the one described for grid failure needs to be performed by the frequency regulation system.

- Ventilation system

The system is a dedicated ventilation system for certain operational areas of the plant. In relation to the frequency regulation system, the ventilation provides the necessary ventilation so the space where the frequency regulator systems are placed is under adequate temperature conditions.

4. Energy considerations

The aim of this section is to analyze the current ESF and the power requirements of the HCP in case of a total failure in the external grid. Consequently, state the minimum energy and instant power requirements for the supercapacitor group. This could be done by analyzing the ESF and choosing a consequent sizing of the new technology with the same minimum characteristics. It makes sense since during the lifetime of the current ESF, it has been able to handle adequately the speed ramp-downs following satisfactorily the given reference. This means that the ESF has both enough stored energy, and power capacity for this application. But in this case, obtaining a general analysis of the energy required by the different components is also of interest. So, both calculations will be done, and the system will be sized accordingly.

4.1. Energy stored and Losses.

First the calculations of the amount of energy stored are performed. For that, the data of the components is used, and all is computed into one final term. The main components where energy is stored in the system is the ESM, the HCP motor, and the primary water flux itself; other minor storages that could be considered are dismissed since they are consider several orders of magnitude lower. Additionally other components intervene in the amount of energy that arrives to the HCP motor, this will be reviewed in the final computation.

In Section 4 there are constant references to energy/power in the shaft or energy/power in the ESF, so it is convenient to explain these terms before they appear. When the mechanical power/energy in the HCP motor´s shaft is used as a reference point, it will be referred as power/energy in the shaft. While if the balance or calculations are referred to the ESF it will be mentioned accordingly.

4.1.1. ESM

The ESM within the ESF is the main point of energy storage of the system. To calculate the kinetic energy available in the energy storage, motor the following equation is used (were the value for the inertia 198kgm^2 is taken from data specifications).

$$E(t) = \frac{1}{2} I w^2 = \frac{1}{2} * 198 * \left(1800 * \frac{2\pi}{60}\right)^2 = 3{,}517MWs = 977{,}09Wh$$

As it is mentioned at the beginning of this section, only with the information of the energy and power provided by the ESF a preliminary sizing of the new ESS could be performed. In consequence this information gives order of magnitude of the result expected.

4.1.2. HCP

To calculate the energy stored in the HCP and the motor the calculation is like the one done in Section 4.1.1 for the ESM. But in this case the inertia is the combined inertia of all the rotating mass, which includes the pump and the electrical motor (20kgm^2 – Technical data). And the rotating speed differs.

$$E(t)_{HCP_t} = \frac{1}{2} I w^2 = \frac{1}{2} * 20 * \left(1480 * \frac{2\pi}{60}\right)^2 = 240{,}204kWs = 66{,}72Wh$$

As expected, the energy stored in the HCP + HC motor is less than the one stored in the ESM, but still is of considerable value. It is important to point out that while the energy in the ESF can be extracted as needed, making use of the driver associated, the energy stored in the HCP is dependent on the rotational speed on the HCP. So, the power release is directly associated with the speed setpoint given in Figure 9. Since the speed reference ramp does not get to 0, there will be some power that remains unused from the total kinetical energy stored. Thus, the total energy released by the HCP inertia is the difference between the total and the unused energy. The unused energy can be calculated as follows:

$$E(t)_{HCP_{nused}} = \frac{1}{2} Iw^2 = \frac{1}{2} * 20 * \left(607 * \frac{2\pi}{60}\right)^2 = 40{,}405kWs = 11{,}22Wh$$

Being the energy used in the ramp down:

$$E(t)_{HCP_{used}} = E(t)_{HCP_t} - E(t)_{HCP_{nus}} = 199{,}799kWs = 55{,}5Wh$$

Therefore, around 17 % of the energy stored in the HCP inertia is not used for following the ramp down. All these energy calculations are referred to energy in the shaft.

4.1.3. Water flux

The analysis of the energy stored in the flux is a complex task. And some of the variables that influence how it varies escape the scope of this project. With that said, the water flux energy will be dismissed from the calculations. But it will be taken in consideration when analyzing the results.

4.1.4. Losses

To make a correct comparison, the energy balance will be made on the shaft and later translated to the ESF. This will be done in Section 4.2. To do that, first it is necessary to explain the approach that have taken when handling the losses in different components.

Losses depend on different factors, like the temperature, state of the equipment, power through the equipment in a particular time or even dynamic behaviors of the equipment. In that sense the complexity of analyzing these factors grows as more detail is required. In this case getting the general behavior of this component will be evaluated, being the losses overestimated in most cases. The result obtained will have an intrinsic safetyt coefficient included, and it will be considered during the sizing. In Section 6, the simulations include a more detailed analysis of the dynamics of the losses.

The elements that are of interest for this analysis are the ones present in Figure 9. In particular, the elements to analyze in this section are the ones connecting the ESF to the HCP motor. Those are the ones that will influence the amount of energy loss between the systems, and thus influence the energy needed for the ESF. The losses in each of these elements is analyzed together with and explanation of how the losses have been considered for each of them. It is relevant to note that the ideal case is to perform a dynamic analysis of the losses. For that it would be necessary to have a detailed analysis of how each component behaves at every operating point. This is not the case; therefore, assumptions have been made and the impact of each assumption has been analyzed. As a base, a previous project that studied the losses at full load for the system is used, see [31].

- HCP motor

At the HCP motor there are two factors to consider. First the efficiency from the mechanical to the electrical side η_{HCP}. The working load impacts the value of this efficiency, being normally at peak efficiency for design load and lower for lower loads; in this case there is no data available for the dependency of the efficiency depending on the load. Since this variation is not too high and the smaller the load the smaller the total impact in the calculations, this variation is dismissed.

The second factor is the power factor $(\cos(\varphi))_{HCP}$. As with efficiency, the power factor value has a dependency on the operating point of the motor, but again there is no data available to estimate its value. Considering it constant, in the same way as for the efficiency, for all the operation points. Both assumptions slightly underestimate the losses in this component.

- Cables

The losses in the cables for this analysis can be mostly dismissed since the length of the cable between most elements is small. Nonetheless, the cable between the HCP motor and the output transformer is considerably longer than the rest and has an impact relevant to this analysis. Thus, it needs to be analyzed. The cable resistance per unit area is adjusted with the operating temperature, and the total resistance calculated considering its total area, the length of the conductor and that there are two conductors per phase. This results in the following equation.

$$R_t = \frac{l \cdot r}{n} * (\frac{(235 + T_{op})}{(235 + T_{ref})} = \frac{114 \cdot 7{,}54 \cdot 10^{-5}}{2} \cdot \frac{235 + 70}{235 + 20} = 5{,}14 \cdot 10^{-3} \Omega$$

That is the resistance for both cables together. The power losses at the cable are calculated with the resistance at each cable and expressing the current through the cable in terms of the power as it is seen in the following equation.

$$P_{c\_loss} = 3 * \left(\frac{S_{HCP}}{\sqrt{3} V_{HCP}}\right)^2 \cdot R_t$$

Then the value of the losses at the cable depends on both the rated apparent power consumed at the HCP and the voltage applied to the HCP motor. The apparent power is dependent on the active power required by the pump to run at a certain rotational speed and the power factor of the motor, which is assumed constant. Meanwhile the voltage of the pump is down controlled by the HCP drive maintaining the relation cte=V/f; since n ∝ 1/f, then V ∝ n, being the value of the voltage only determined by the speed at which the pump needs to be run.

- Output transformer

The losses at the output transformer can be calculated based on the short circuit impedance of it. Since there is no data on the resistance and reactance part of this impedance, a value of x_k has been accorded based on inside knowledge and typical values of this kind of technology. The short-circuit impedance, the active and reactive power loss can be approximated as shown in the following equations:

$$Z_{ot2} = \frac{{U_2}^2}{S_M}$$

$$P_{ot\_loss} = \left(\frac{S_{HCP}}{\sqrt{3} V_{HCP}}\right)^2 \cdot Z_{ot2} \cdot \sqrt{1 - {x_k}^2}$$

$$Q_{ot\_loss} = \left(\frac{S_{HCP}}{\sqrt{3} V_{HCP}}\right)^2 \cdot Z_{ot2} \cdot (x_k)$$

The impedance Z_{ot2} is referred to the secondary side of the transformer since the current used to calculate the losses has been chosen to be the one in the secondary side of it. Again, the current is being calculated from the relation between the apparent power and the voltage at the HCP motor. This value also has a small variance depending on the load of the transformer but serves as a good approximation to this pre-study.

- Sinusoidal filter, HCP drive & ESF drive

For the last three components, the only data available is the total power loss at nominal power. Since no other data has been found, a somehow conservative decision of assuming the three of them constant during the whole operation area has been taken.

Taking all the previous information into consideration, the values of losses that will be considered are the following:

Table 2. Punctual losses between HCP motor and ESF.

Parameter	Value
$\cos(\varphi)_{HCP}$	0.8
η_{HCP}	0.87
R_{cable}	0.00514 Ω

Z_{ot2}	0,02189 Ω
x_k	3,7%
$P_{loss_{Sfilter}}$	10 kW
$P_{loss_{HCPdrive}}$	22 kW
$P_{loss_{ESFdrive}}$	14 kW

Insight into both the energy stored in both the HCP and the ESF inertia and the data for the different losses of the elements and approximation to the energy balance can be made. This is performed in Section 4.2. The losses in Table 2 are only used for the approximation of the energy balance to estimate the energy requirements and to do a preliminary sizing. For simulations in Section 6 the dynamics of the systems are further considered.

4.2. Energy requirements

The energy requirements for the system are mainly two. The first one is the minimum energy needed to speed down the pumps according to Figure 10 in the most unfavorable case (the last two pumps to be disconnected). The second is the power demand profile to carry out this task, in which peak power is the most relevant figure. Additionally, a review of the tests performed in the actual NPP will be analyzed and used as support during this section; aiming to validate and comparing the calculations to the results obtained in field-tests. The same reference systems explained in Section 4.1, energy/power in the shaft and on the ESF will be used.

4.2.1. Energy evaluation

To do a preliminary sizing of the new ESF an assessment of the current system is used. The aim of this assessment is obtaining the evolution of energy at the different points of interest of the system and the power necessary at every point in time. In Section 4.1 the amount of energy available and the main losses of the system are described. But the power required to follow the speed curve is still to be determined. To relate the speed reference curve available in Figure 10 information about the head circulation flow in relation to the pump is needed. To do that the concept of pump-curves has been used.

- Speed-Power curve

From the system curves available the amount of information obtained is really limited. There is no curve that directly relates the speed of the pump and the electrical power consumed. And the available data is based on a graph with low detail. To minimize human error when reading the graph, a nonlinear optimization tool has been used to approximate this curve. For that, the data of the nominal point of operation and the operation curves of the motor for the initial system will be used. The data available at the graph is down to 1020 rpm – 320kW. For velocities under 1020 rpm there is no data available, the only limitation is that at 0 rpm the power should be 0 kW. To cover that area a set of 4 points are introduced extrapolating linearly between 0 and 1020 rpm. Table 3 shows the general data of the optimization.

Table 3. Speed-Power points obtained and estimated.

Data Points	P_coef	N(rpm)	P (kW)	P´(kW)	(P-P´)^2	P_coef*^E2
P1	2	0	0	-57,3	3282	6565,2
P2	1	200	63	62,6	0,009	0,009
P3	1	400	125	125,5	0,0003	0,0003
P4	1	600	188	165,2	530,3	530,3
P5	1	800	251	215,9	1231,6	1231,7
P6	3	1020	320	324,9	23,8	71,5

P7	3	1120	390	404,7	215,1	645,4
P8	3	1200	470	486,2	261,9	785,9
P9	3	1350	640	689,5	2449,3	7347,9
P10	3	1400	745	773,9	833,4	2500,3
P11	3	1450	862	867,4	29,6	88,7
P12	10	1480	977	928,2	2380,1	23800,9

In Table 3 data for 12 curve points is given. The field P_coef contains the penalty coefficient assigned to each of the curve points. N(rpm) represents the speed at each of the data points. P(kW) and P´(kW), represent the real input data of power for a given speed and the power calculated from the obtained equation curve (called the cubic optimized curve). And the last two columns give the squared error and the squared pondered error with the penalty coefficients used for the nonlinear optimization.

The selection of the penalty coefficients is arbitrary and has been fined tuned considering the available data. From the graphs available only data points 6 to 12 were extracted. For the sake of obtaining a reasonable result in the lower spectrum of speeds a linear extrapolation was done to generate points 1 to 5. In that sense, more importance has been given to the "real" data points with use of the penalty coefficients and less to the extrapolated points. Point 12 has extra relevance since it is the only point of which there is accurate data for the current system.

The goal of the optimization is finding the values A, B, C and D, which minimize the summatory of the squared errors multiplied by the squared coefficients. Being A, B, C and D, the parameters of the cubic equation, that relates power and speed.

$$P(n) = A \cdot n^3 + B \cdot n^2 + C \cdot n + D$$

After fine tuning the coefficients and running the optimization the result obtained is the curve shown in Figure 11.

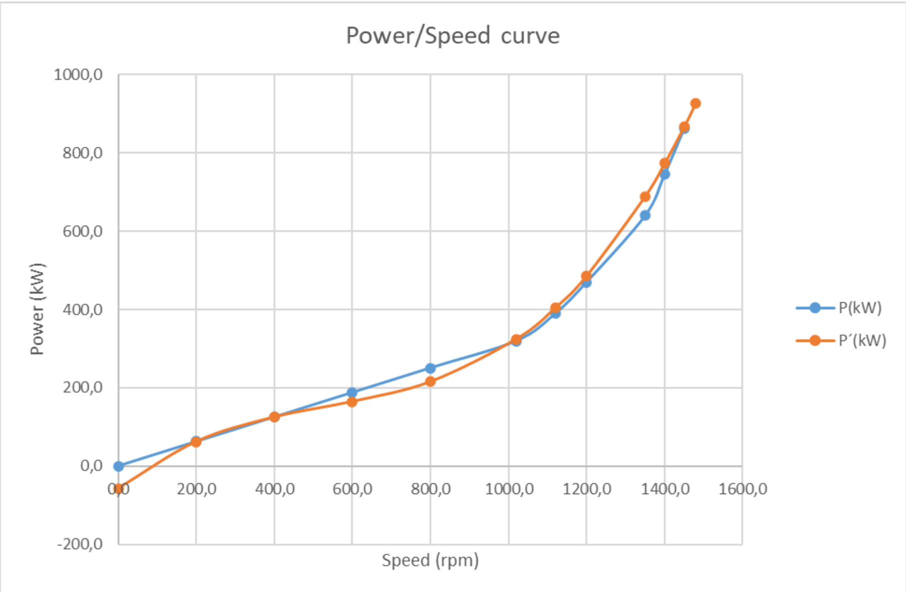

Figure 11. Power-Speed curves for the HCP motor.

Figure 11 shows, in blue, the plot of the real input data for speed and power; and in orange, the data resulting from the cubic optimized curve. The optimized curve gives negatives values of power for values close to 0 speed which is not reasonable. Nonetheless, this is for operation speeds out of the range of the down-control of the pump so it will have no effect in the analysis. And by admitting this negative value, the obtained curve gives a closer behavior to the data given. The coefficient values for the curve equation are given in Table 4.

Table 4. Coefficients for the Speed-Power curve.

Coefficients	A	B	C	D
Values	7,09E-07	-0,001139348	0,799221	-57,2942

With the values for the equation relating power and energy obtained, the calculations of power and energy at the ESF can be done, including the power profile and total energy stored in the ESF.

4.2.2. Power requirements

When selecting the basic characteristics of any ESS for a particular application, it is important to consider not only the energy stored but also the power requirements of the application. It must be ensured that the given ESS can supply the maximum peak power required by the system and the necessary power during the whole discharge.

Focusing on the reference of the ramp down control in Figure 10, the system maximum power feeding from the ESF is expected during the interval t1-t0. During that time the ESF must be able to supply all the power that was being supplied by the grid at the nominal load point, since the energy stored in the flux and the HCP motor is kept constant. The rest of the intervals require a smaller power capacity. If there is a ramp down (a slowdown) on speed, the energy stored in the HCP motor and flux is also being released; and if there is a constant speed interval at a lower speed, the power from the ESF is also going to be smaller (since less pump speed means less power consumption). Analyzing the energy through the system for 7,88 seconds, the most demanding ramp down, the power balance in the HCP shaft can be seen in Figure 12.

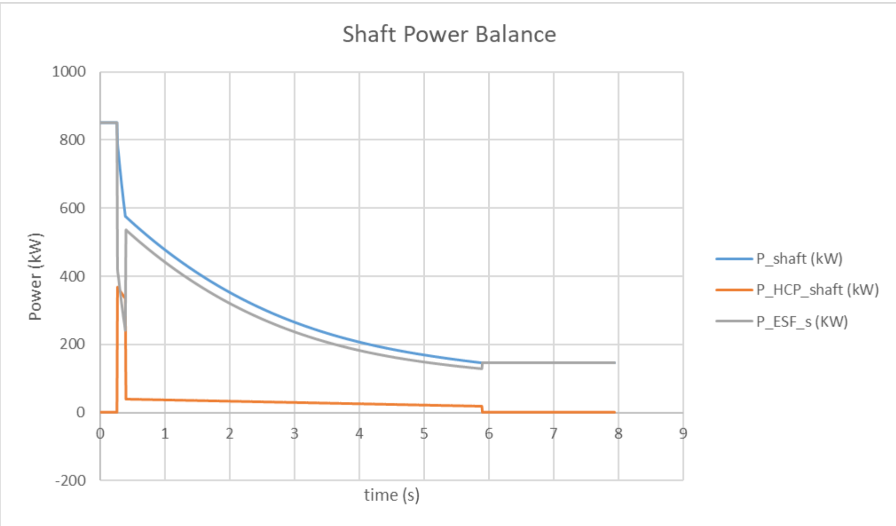

Figure 12. Power balance at the HCP shaft.

Figure 12 represents the evolution of the power required and released by the main sources to follow the ramp-down in speed to ensure the safety of the core. The blue line represents the mechanical power required in the shaft to follow the ramp-down in speed reference. It can be seen as a direct application of the power-speed previously obtained (see Figure 11) on the speed reference of the system. The orange line gives the power supplied by the HCP motor when slowing down. This curve is dependent only on the inertia and the variation of speed. And lastly, the grey line is the power required at any instant from the ESF referred to HCP shaft. It comes from the difference between the energy required at the shaft and the power provided by the HCP motor inertia.

As mentioned, the grey curve in Figure 12 gives information about the power that the ESF need to supply so the system is run as expected. Nonetheless, this is the power referred to the HCP shaft, all the losses between the HCP and the ESF need to be considered to obtain the actual power provided by the ESF. Including the punctual losses as indicated in Table 2, the power curve in the 7,88 seconds interval is the given in Figure 13.

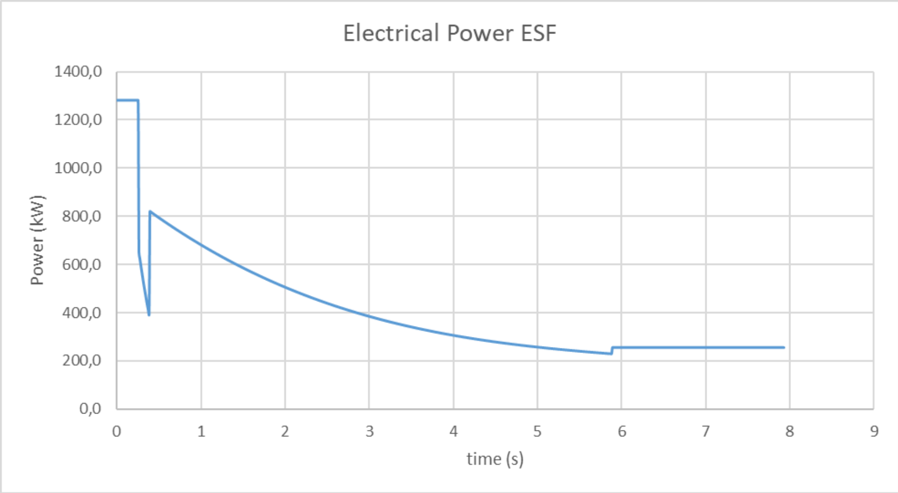

Figure 13. Power requirements at the ESF curve.

Figure 13 shows the power needed from the ESF referred to the ESF drive entry. This serves as a base to set the minimum instant power that the ESF technology needs to supply to fulfill the speed curve requirements.

4.2.3. Total energy necessary

Once the power curve is obtained, it can be used to integrate the amount of energy strictly necessary to ramp down the systems, as well as the different energy contributions from the different systems with the current solution. The energy evolution in the main systems is shown in Figure 14.

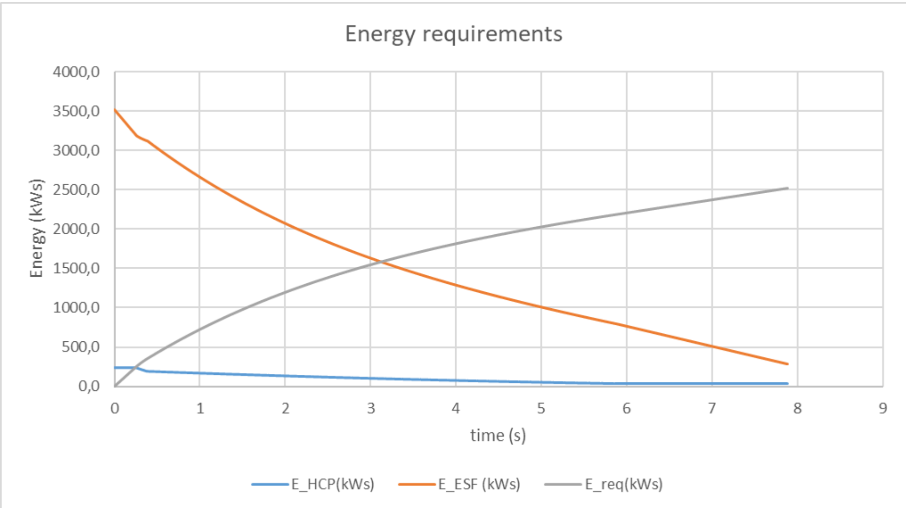

Figure 14. Total energy evolution.

Figure 14 shows the evolution of the total energy stored in kWs in the ESF and HCP inertia, and the total energy in kWs consumed at the HCP motor. In this case the reference of each energy is directly referred to their own reference system. In that sense, the blue line shows the evolution in rotational energy stored in the HCP motor. The grey line represents the total electrical energy consumed by the HCP motor. And the orange represents the evolution of the total energy stored in the flywheel. Doing total energy balance at time 0s and time 8s in Figure 14, it is interesting to note that these curves show that the total losses are slightly lower than 1000 kWs, which correspond to around a 25% of losses during the ramp down.

From the calculations made it is shown that the current ESS has enough energy to perform the longest ramp down protocol following the speed curve references. That fact is confirmed by actual tests made on the system that are summarized in Section 4.2.4. An analysis on how to interpret the calculations and which conclusions can be derived from them for the sizing of the new ESF are done in Section 4.3.

4.2.4. Test overview

Tests have been carried out during the lifetime of the system to confirm that the requirements were sufficient to carry out the expected output, as the calculations made point. This test is relevant since it shows the actual response of the system in place in the case of a complete grid fail. In this subsection a short introduction to how the test has been made, the results, conclusions and a comparison with the calculations previously done are made.

The test aim to analyze if under a complete failure of the outside grid, the ramp down control of the speed in the HCP motor is made according to the speed reference given and pretends to give insight about the behavior of multiple parameters both electrical and from the HC flux.

To do that the protocol followed is an actual test on the system. Under the system running at operational point (1480 rpm), a failure on the outside grid is simulated by interrupting the power supply from it and the response of the system is measured, doing the ramp down in the eight pumps and consequently turning off them in pairs in periods of 0,5s.

The result of the tests is satisfactory, it shows that the ramp down fulfills the minimum requirements and therefore the ESF system is adequate to cover the ramp down in case of a complete failure of the outside grid. Additionally, it shows that due to the control time clocks an additional retard is added to the ramp down and that still the system is able to react the way it is expected. This tests alone does not serve to validate the exact result obtained in the calculations, but it allows this pre-study to assume that the ESF given has indeed enough energy to cover the ramp down of the HC pumps and gives a good reference for the sizing of new technologies.

4.3. ESS sizing

The requirements for the ESS size and characteristics are based mainly in the total energy storage needed and the power capacity. After the requirements and basic characteristics are well defined a commercial model can be analyzed.

4.3.1. General considerations

In this section the general considerations and assumptions made for the sizing of the supercapacitor are specified. The main requirements to fulfill to ensure the correct functioning of the system are the power capacity and the total energy stored. These two and the assumptions made during the sizing of the supercapacitor are studied below.

- Power Capacity

The selected ESS must fulfill two minimum requirements during its operation time. The first one is having a minimum peak power capacity over the maximum system's needs. And the second one is being able to supply the necessary power required at any given time.

The maximum power capacity is given at the first stage after the external grid drops. Due to the speed curve reference the operation point is maintained to nominal for 0,25 seconds, and then start the speed-down process. The value of 0,25 seconds is used for the flat-top and not 0,55s since a full fall of the external network is considered, which is the least favorable case. The nominal electrical power is 977 kW, but the power provide by the ESF must overcome the losses in between, and according to the calculations made (see Section 4.2.2) the peak power during that interval at the ESF output is 1282,7 kW.

The current ESF has the advantage of having almost no limit of power output, since it only depended in the material integrity of the axis and other mechanical elements. When defining a new ESF solution based in supercapacitors, this is a deciding design factor.

The second requirement is that the selected technology can provide the necessary power in the whole ramp-down interval. Or what is the same, that the ESF can supply the power as indicated in Figure 13.

Normally to both power requirements a security margin would be added. As it is shown in Section 4.3 the supercapacitor is designed for end of life (EOL) conditions which already takes into consideration aging and tolerances effects. Additionally, during the sizing an extra security factor is added due to the design methodology. Therefore, no extra "security" factor will be added for the design, and an evaluation of this decision will be done in Section 8.

- Energy stored

The main requirement regarding total energy stored in the new ESF is that it has enough energy to ensure that the ramp down process can be fulfilled. It is important to include a security coefficient when sizing an ESF, and it is even more relevant when it is used as a backup security system, as it is in this case.

To calculate the energy required for the ESF two paths can be taken. The first one is just assuming that the new ESS must have at least the same amount of energy storage capacity as the previous ESS and refer to the plant tests made on the system to justify that is enough (See Section 4.2.4). In this case the security coefficient mentioned would be dismissed since it is considered that it was already included during the sizing of the previous ESS (the energy storage motor, see 4.1.1). In that case:

$$E_{ESS} = E_{ESmotor} = 3517{,}5kWs$$

The second approach is to obtain the necessary energy for the new ESF from the integration of the power-time curve in Figure 13. By doing that, the total energy required referred to the ESS output is 3249,3 kWs. The assumptions to get to this result will be discussed later, but it serves as a relevant figure to do the sizing of the new ESS. Based on that number together, the security factor that was included in the design of the current ESF can be calculated as:

$$Cfactor = \frac{E_{ESmotor}}{E_{req}} = 1{,}0825$$

For the sizing of the supercapacitor group no coefficient will be considered for the total energy stored. The reasons are the same ones as the ones given for the power requirements. The sizing of the supercapacitor group includes the EOL derating factors, and the final energy stored is bigger due to the sizing methodology. Nonetheless an analysis of this decision will be done in Section 8.

- Other assumptions

The main parameters considered in the sizing of components were introduced in Section 2.4. It is important to specify the values of this components beforehand so the sizing of the supercapacitor group can be performed, this is done in Table 5.

Table 5. Supercapacitor sizing parameters.

Parameter	Value
Cell voltage	3 V
Utilization factor	90%
Capacitance derating	70%
ESR derating	200%
System maximum voltage	812V/250V/162V
Total time	7,88 s

Table 5 sets the design values for the main sizing parameters. The most commons values for voltages in industry solutions are between 2,3-3 V, see 2.4.4; being this one a high voltage application, a 3 V cell has been selected to reduce the amount of cells in series. The values for the capacitance and ESR derating, and the utilization factor, are also common values for this type of technology, see 2.4.3. Finally, the system maximum voltage has been selected to match the nominal voltage of the intermediate line. Although the intermediate DC line has a voltage of 1000V, the voltages that have been considered for the design of the supercapacitor are 812V, 250V and 162 V. Calculating different voltage ranges gives flexibility to decide for a final alternative.

4.3.2. Sizing methodology

In Section 2.4.3 some sizing methodologies were presented to explore different ways to find the adequate solution for this project case. Nonetheless, any of the methodologies presented adjust adequately to this project. This is mainly since the power drawn is variable on time. Because of this, the sizing protocol has been adapted specifically for this case. And the process step by step is the following:

- Step 1. Capacity requirements.

The requirements of the project do not adjust to a typical energy back up problem. Nonetheless, the requirements can be somehow adapted to the entry values of an energy back-up problem. To do this the maximum power needed is selected to be the maximum power required by the ESF. And the backup time is selected so the total energy necessary is fulfilled. That way the resulting capacitor group will be able to provide all the energy necessary at the given maximum power. The EOL minimum required capacity can be calculated by the following expression:

$$C_{SC_{EOL}} \geq \frac{2 \cdot P_{BackUp} t_{BackUp}}{V_{max}^2 \cdot \left[\frac{\alpha_B + \sqrt{\alpha_B}}{2} - \frac{1-\alpha_B}{2} \cdot \ln\left(\frac{1+\sqrt{\alpha_B}}{\sqrt{1-\alpha_B}}\right)\right]}$$

To obtain rated values of the minimum capacity this has to be corrected by the capacity derating factor.

$$C_{SC_{Rated}} = \frac{C_{SC_{EOL}}}{Coef_{C_{derating}}}$$

- Step 2. Number of capacitors per string.

Since a maximum system voltage has been selected, the number of supercapacitors in series are selected to fulfill that voltage.

$$number\ of\ cells\ in\ series = \frac{V_{max}}{V_{cell}}$$

- Step 3. Initial number of parallel strings.

Add parallel strings until meeting the requirements of minimum capacity obtained in Step 1.

$$num\ of\ cells\ in\ parallel = RoundUp\left(\frac{C_{pack}}{C_{cell}} * num\ of\ cells\ in\ series\right)$$

-Step 4. Resistance requirement.

Do the calculation for EOL maximum pack resistance, and calculate the maximum rated resistance based on that value.

$$R_{\max_{rated}} = \frac{R_{\max_{EOL}}}{Coef_{R_{derating}}} = \frac{(1-\alpha_B) \cdot V_{max}}{4 \cdot P_{BackUp} \cdot Coef_{R_{derating}}}$$

Check that the equivalent series resistance is smaller than the maximum rated value for the selected number of strings. If not augment by one the number of strings and recalculate the resistance until the requirement is met.

- Step 5. Power iteration and recalculation.

In the initial back-up power selected, the value of power was assuming that there were no losses in the supercapacitor. Nonetheless, the ESR introduces losses in the system that are variable with the square value of current. To add the supercapacitor losses an iteration process between the value and the value plus losses needs to be performed. Once the maximum power needed including losses is obtained, a recalculation from step one needs to be done to check that values of the sizing of the supercapacitor group do not change.

4.3.3. Sizing of the Supercapacitor group

The initial idea for the sizing of the supercapacitor was to do it in collaboration with ABB Strömberg since it was a possible manufacturer of the solution. Finally, this option was not possible to carry out, so a new approach has been adopted. After analyzing different manufacturers and different options of supercapacitor cells from a company named "Skeleton Technologies". The types of cells used are the SCX5000 (5000F, 3V, 0.20mOhms) and the SCH3400 (3400F, 3V, 0.24mOhms), the data sheets for both components can be found in [33].

The sizing of a supercapacitor group has a high dependency on the conditions imposed by the system. Since no DC-DC system has been selected, there is no specific maximum and minimum voltages for the supercapacitors, which is a basic parameter for the design of the supercapacitor group. As explained in Section 4.3.1, maximum voltages of 812V, 250V and 162 V have been considered to study different possibilities of SC arrangements.

Four cases have been analyzed to see different options available. The first option is a solution for 250V using the supercapacitor cell SCX5000. The second option uses the same cell, SCX5000, but for a maximum voltage of 162V. The third option uses a cell SCH3400 for a maximum voltage of 162V. And the last one uses the same cell, SCH3400, but for a maximum voltage of 812V. The general results for the sizing of the different cases are summarized in Table 6. Supercapacitor group result characteristics: Cases 1, 2, 3 and 4.Table 6.

Table 6. Supercapacitor group result characteristics: Cases 1, 2, 3 and 4.

	Case 1	Case 2	Case 3	Case 4
SC cell model	SCX5000	SCX5000	SCH3400	SCH3400
Max Voltage (V)	250	162	162	812
N° cells series	84	54	54	272
N° cells parallel	8	9	10	9
N° of cells	672	486	540	2430
Eq. Cap. (F)	476,19	833,33	629,63	113,33
Eq. Res. (Ω)	0,0021	0,0012	0,00124	0,0069
Stored E. (Wh)	4133,60	3037,5	2295	10378,56
Usable E. (Wh)	3720,24	2733,75	2065,5	9340,707
Usable E. (kWs)	9375	6889	5205	23538,58
Eq. Cap. EOL (F)	333,33	583,33	440,74	79,33
Eq. Res. EOL (Ω)	0,0042	0,0024	0,00248	0,0138
Stored E. EOL (Wh)	2893,52	2126,25	1606,5	7264,99
Usable E. EOL (Wh)	2604,17	1913,63	1445,85	6538,49

Table 6 shows the results for the basic characteristics of the three cases analyzed. It gives information on the distribution and number of supercapacitor cells. It also gives information about the equivalent capacitance, resistance and energy stored for both the rated and the EOL cases.

The four options presented are valid for this application. The selection of one of the four options or the study of new design alternatives would depend in other components. The first case results in a system slightly over dimensioned, with a high number of cells that would imply a bigger cost. The second option suits the application better, lowering the voltage allow for less total capacitors and thus probably minor price. Nonetheless, both this and the third solution imply that current entering the DC-DC is higher. The third solution is probably the one that makes better use of its capacity compared to the requirements, although it has more total cells than the second one, each unit cell is probably cheaper. The last solution used a much higher voltage what could reduce the current through the ESF system considerably, that makes simpler the sizing of cables and easier the selection of a DC-DC converter. At the same time the difference of voltage with the DC intermediate line is smaller than in other cases what makes easier the conversion and results in a more stable system. On the other hand, the number of cells of this solution is several times higher than in the other cases leading to a higher investment cost.

To continue with the pre-study case 4 is selected. Although it has the higher investment cost, it results in a more stable and reliable option. The lower use of each of the cells reduces the possible maintenance topics and other issues that could appear due to fast voltage or current fluctuations. Additionally, the same manufacturer has modules of 54 cells with the same type of cell which gives additional information when estimating size and weight. Referring to the sizing methodology, see 4.3.2, the high number of cells in parallel is due to “step 4” which refers to the internal resistance.

4.3.4. Sizing of other components

The objective of this pre-study was focused on analyzing and pre-sizing a supercapacitor solution for the ramp-down system of the HCP pump. Nonetheless, the DC-DC converter plays an essential role for this solution and therefore it´s important to review it.

- DC-DC converter

The sizing of the DC-DC converter and the supercapacitor group have to be sized together, since the specifications of one need to fit the others. Since the peak power necessary is higher than the usual standards for this type of static converter, a DC-DC converter needs to be manufactured specifically to meet the needs of this application. Since there is no information about the limitations that this could impose, or what limits should be considered, the sizing of the DC-DC converter is made to fit operation of the supercapacitor solution selected. The characteristics of the DC-DC converter needed are gathered on Table 7.

Table 7. Required characteristics for the DC-DC converter sizing.

Parameters	Minimum value
Minimum rated power	1282,7 A
Voltage side 1	1000 V (DC)
Current side 1	229,4 A – 1282,7 A
Voltage side 2	675,98 V – 812 V
Current side 2	300,3 A – 1624,7A

Table 7 gathers the basic requirements that the selected DC-DC converter needs to present. Side 1 refers to the common DC line of the system, while side 2 refers to the ESF side.

The values required for the current on the secondary side are considerably high but still within a reasonable range. With e.g. case 1 the current on the secondary side would be appr. 5300 A. This is much more of a challenge. This is the reason why high voltages are often used.

5. Type solution

The main objective of this project is obtaining a solution that serves as a base for future work if the system decides to be developed. Once the system has been analyzed and the requirements for the sizing of a new ESS obtained, a type-solution can be presented. In this Section a proposed solution is presented, the selection of suitable industrial alternatives is made, and other relevant aspects are introduced.

5.1. Proposed solution

The proposed solution introduces changes in the ESF systems attached to the HCP motor systems that control the HC flow in the reactor. The current solution is based on an AC energy storage motor connected to a common DC bus through an AC/DC drive that helps control the power delivered. A scheme of the current system is available in Figure 9.

The new proposed solution is based in supercapacitors as energy storage, and it is connected to the same DC bus available in the current system through a DC-DC drive that implements the necessary control strategies to ensure the supply of power required.

5.1.1. Electrical scheme

The proposed solution electrical scheme is show in Figure 15.

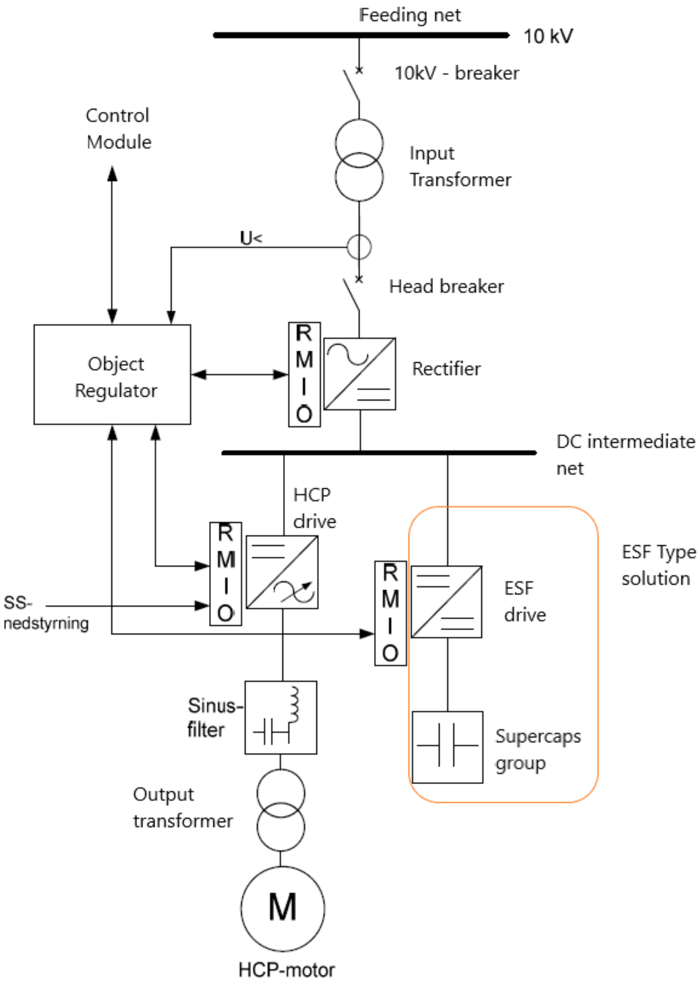

Figure 15. Electrical scheme for the new ESF type-solution.

As it is shown in Figure 15, the solution only requires a change in the ESF itself, the rest of the system remains unmodified. The previous ESF is replaced by an ESF composed mainly by a supercapacitor group and a bidirectional DC-DC driver that helps to control the power transfer to the SC group. The sizing of this components can be studied in Section 5.2 and Section 5.3.1 respectively.

Regarding the connections with the rest of the system. The DC bus is still adequate after the change since the power flow remains equal and the ESF driver will be sized accordingly to fit the DC bus voltage. Apart from that, the control strategy would need to be adapted to the type of technology to ensure the correct functioning of the new solution, this will be further explored in Section 5.3.3.

5.2. Supercapacitor

The selection of the supercapacitor is based on the sizing made in Section 4.3. The commercial solution selected should, therefore, cover the technical requirements described regarding power and energy. The collaboration expected from ABB Strömberg have not been possible. As a solution technical data from the company Skeleton technologies has been used to develop a suitable solution. The sizing and thus this proposed solution is based on the data sheets of specific products of this company. In case of considering other companies or components for a future project, adaptations in the calculations should be done or similar components should be selected.

As it is explained in Section 4.3.3, the designed process resulted in a solution of 2430 cells of the model SCH3400, in a combination of 9 strings in parallel of 270 cells in series (data sheet of the component in [33]). The basic pack characteristics can be found in Table 6. Figure 16 and Figure 17 show the evolution of the values of current, voltage, power and energy for the system selected.

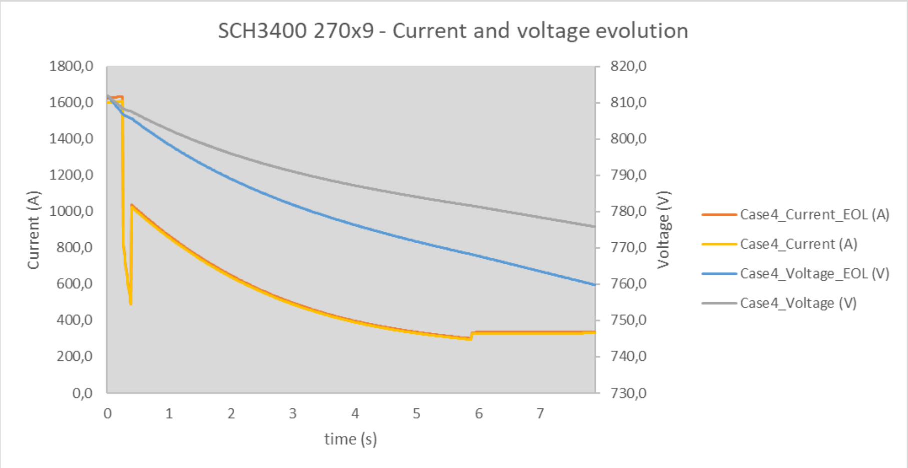

Figure 16. Current and voltage evolution during ramp down for case 4.

Figure 16 shows the voltage and current for both the rated and the EOL specifications for the system selected. The behavior of the voltage is as expected, the voltage is reduced as the discharge is taking place. During the lifetime of the module, the voltage drops more in magnitude as it discharges due to the drop in the capacitance value. The current evolution describes a similar shape to the power requirement which is reasonable. As the lifetime of the module approaches its end the supplied current needs to be higher to compensate for the drop in voltage mentioned above.

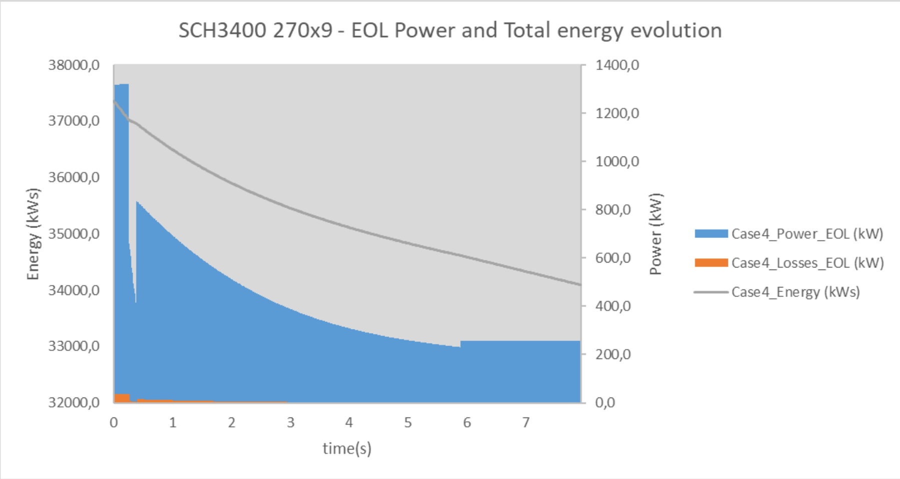

Figure 17. EOL Power and total energy evolution for case 4.

Figure 17 shows the power, power losses and total energy stored for the EOL conditions. The situation EOL require que maximum peak power delivered by the supercapacitor group 1319,3 kW. This increment compared to the maximum power required shown in Figure 13 is due to the losses at the ESR of the supercapacitor group. Close to EOL conditions the ESR reach its maximum and therefore the losses too, both because of a bigger ESR and because the general increase in current, see Figure 16.

The same manufacturer company used to select the supercapacitor cells to have module solutions of the cell selected. The module "SkelMod 162V62F" is a module formed by one string of 54 cells in series and 1 in parallel (54s1p), data sheet available in [35]. Additionally, the same company present integrated solutions up to 10 modules named "SkelGrid 2", design for short-term energy storage and grid stabilization. This technology ensures modularity, mechanical protection, electrical protection, cooling and control and monitoring of many parameters inside the modules; data sheet attached in [34].

The "SkelGrid 2" will be taken as a proposed solution with 45 modules "SkelMod162V62F" connected in 9 parallel rows of 5 modules in series. This configures the system designed of 54x10 supercapacitor cells SCH3400 in a modular solution. It also gives insight about the weight and size of the final solution which is valuable for sizing other parts of the project.

5.3. ESF Elements

The supercapacitor group constitutes the unit of energy storage of the ESF. Nonetheless there are other new elements that must be considered when projecting the proposed solution considered. In this section those elements are explored and considerations about them are made.

5.3.1. DC-DC drive

The proposed solution for this component should fulfill the requirements mentioned in Table 7. Other functions that must include are, be able to work bi-directionally to charge and discharge the supercapacitor group and have the functionality to implement control the power flux according to a certain control reference, aiming on doing both, the charging and discharging of the supercapacitor group.

Within the solar power industry similar power solutions have been found. Although these solutions do not fit the requirements in current, they will be considered as base for the expected physical size of a future solution. To get order of magnitude to develop some of the next sections further.

The model selected is the "DPS-500 DC-DC converter". It has a maximum rated power of 500kW, voltages range from 100-1500V for both entry and output, and a maximum current rating of

500 A (Data sheet attached in [12]). The main specification that isn´t fulfilled by this chose is the maximum current rating (see Table 7).

For this case, three DC-DC converters of this type should be placed in parallel. The peak power in EOL conditions would be a little bit higher than the rated current but since this current is just present in the worst conditions and just for a period of 0,25s this could be acceptable. Since no contact with a supplier has been taken no confirmation of this can however be given. Nonetheless it is assumed possible from here on.

5.3.2. Cables and protections

With the current solution 3 phase AC connections are being used at the ESF, with the corresponding electrical protection. This would need to be adapted to the new solution. A new DC cable capable of withstanding the power requirements given in Figure 13 must be included, with the corresponding protections.

5.3.3. Control systems and algorithms

The current solution uses a remote input-output module (RMIO) to communicate the control module with the AC/DC drive of the ESF. The compatibility of this module should be analyzed and in case of incompatibility a suitable replacement needs to be found. The same must be done with the measurements given by the supercapacitor group, as well as adding protocols and algorithms to process the new available data and react to it accordingly. The “SkelGrid 2.0” has a CAN bus 2.0 dedicated for this type of communication.

Modification in the control algorithm must be considered to adapt to the new technologies that form the ESF and the new connections to them. A new control strategy must be implemented to control the charge and discharge of the supercapacitor group, and adaptations in the control of the other drivers have to be also made. Also control strategies considering the internal state of the supercapacitors should be considered to ensure the correct functioning and maintain the desired lifetime.

Trying to give a detailed control strategy of the frequency control system at this stage of the solution is not reasonable. But considering the system has predictable behavior, solutions with predictive control methodologies could be a great option to consider.

5.3.4. Ventilation system

Both the supercapacitor group and the DC-DC converter need cooling to ensure good performance and keep the integrity of the components. The SkelGrid is designed so natural cooling is enhanced, and the DC-DC converter has a forced cooling system in-built.

To ensure that the cooling of the components is done appropriately, a dedicated ventilation system should be projected to keep the space allocated for these components at ambient temperature during operation.

5.4. Safety

A detailed safety analysis is mandatory to assess the possible scenarios in which the system could affect the safety of workers or compromise the integrity of the structure or other components in the surroundings. A recent report from “Synergi Life” notifying a HSSE/PS Incident alert describes an electrical explosion in condensator battery in High Voltage interconnection facility [36]. For the similarity of the technology makes it more important to review the safety aspect of this project. This Section aims to analyze the causes, if there are so, in which the system could lead to a safety threatening situation and how to prevent them and reduce the impact in case they get to occur.

5.4.1. Causes overview

The overview presented here are based on a review on the safety report mentioned [36], and the limited literature that has been found on the topic[16][32][1][10][9]. This section has the purpose of give some insight about some threads to consider when analyzing safety measures.

- Overvoltage. Supercapacitor lifetime is highly dependent on the voltages applied [42]. Working at voltages higher than the rated will led to a noticeable decrease in lifetime and performance. Cases of extreme overvoltage that are not cleared immediately could result in the incapacitation of some supercapacitor cells with possible overheating of the components.
- Undervoltage or overcurrent. The main problem of undervoltage is not the low voltage itself. When delivering constant power, the supercapacitor provides a lower voltage as it is discharged, and the lower the voltage the higher the current. Overcurrent due to that or other phenomena, has a damaging effect on the cells accentuated if it is prolongated during time.
- Reverse polarity. Fast discharges of the cells can sometimes lead to reverse voltages applied to the borders of the SC cells. This could cause negative effects on the SC lifetime. Nonetheless, reverse voltage protection is included in most supercapacitor modules and that should completely remove any problem arising from this cause.
- High temperature operation. It has been mentioned many times, temperature is one of the factors that have the worst influence in the SC lifetime [42]. In theory it should only affect the performance and not cause any instant damage that could influence the safety of the installation.
- Mechanical damage. Mechanical damage of the cells could lead to general malfunctioning of the cells and can become a thread to safety in particular if this damage is made under operation.

In general, after the review of the pertinent literature, it is adequate to say that EDLC supercapacitors present a high safety over a wide working range of temperatures and charges. Regarding the HSSE report [36] not enough data is available to determine if there could be a similitude to the case of this project. But based on the images available in the report the technology looks like a completely different solution, with a big size capacitor probably not intended for energy storage but for signal filtering before the storage. In the unlikely case that an explosion occurs due to extreme conditions of the causes exposed above, the size of the explosion would not cause any structural damage being the start of a fire the worst-case scenario foreseen.

Most of the cases of poor management of the SC group lead to a reduction in lifetime, if extreme conditions are applied overheating can appear and liberation of smokes or even start of a fire could arise if those conditions were not cleared effectively. Working under controlled conditions, with the necessary preventing measures and with an adequate supercapacitor management system, the safety of the supercapacitor and, in general, of the ESF group do not differ from the one expected for other electrical power system.

5.4.2. Prevention methods to ensure safety

The possible causes that could lead this system to pose a risk to safety have been explored in Section 5.4.1. In order to avoid these risks for happening here are some considerations that are important to take into account:

- Electrical protection. Besides the necessary protection to ensure that prevent that any operator can get in contact with a life-threatening electrical charge. Special attention on clearing faults responsible of high voltages or currents that can damage the supercapacitor group should be taken.
- A supercapacitor life-management system like the one included in “SkelGrid 2.0” or similar is desired. Having constant tracking of internal variables and an indication of the

aging of the cells helps to prevent any malfunctioning due to age-related effects. This normally includes inside temperature monitoring which can be used to add extra protection in the control systems.

- Mechanical separation. Both the supercapacitor group and the DC-DC system have an in-build protection casing that should serve as protection against the most unexpected mechanical damage. Placing the equipment in a dedicated room separated from any moving or rotating elements would be appropriate.
- Charging after complete discharge. This is normally taken into consideration in life management systems but not in our case solution. In the case solution proposed the supercapacitor has the possibility to get completely discharged. Either after ramp-down of the system due to a stop of the reactor or at a need of maintenance stop (preventive or remedial). In these cases, as well as when the supercapacitor is first installed, the charge conditions have to be carefully taken into consideration.

In case the prevention protocols fail to work three main scenarios can be foreseen with decreasing likelihood. The first one is a failure in the equipment that does not lead to any compromise in security. The second one is a failure in equipment that leads to failure of the component itself, limited dimension fire and gas emissions, but do not compromise the integrity of any other component or structure, and do not mean any imminent thread to operators' safety. And the third is a component failure that results in an explosion or fire that can lead to structural damage, damage other components, or pose an imminent danger to the safety of people around. Safety protocols considering any of these three scenarios should be planned if the project is finally carried out. Additionally, the following measures would need to be implemented to limit the impact of any of the mentioned scenarios.

- Fire isolated space. In the unlikely case of a component partial or complete burnout it is important that the ESF is in a dedicated space forming its unique fire area.
- The evacuation of any produced gas due to partial decomposition of the components should be evacuated through a ventilation system. This can be considered in the same ventilation system dedicated for space temperature control, or otherwise a dedicated ventilation system should be planned. Although not detailed information about the gases in supercapacitors have been found, it is expected that these are considerably less dangerous than the ones caused by chemical batteries, and comparable to the burndown gases produced by any other electrical components.
- Extinguishing equipment. As in any other situation where fire could take place, extinguishing equipment has to be placed in the room in order to mitigate a possible fire. A fire detection system is necessary and the need of an automatic system for putting out the fire should be evaluated.

Giving a personal evaluation, the chances of any of these situations happening and being critical to security are low if the system is sized with an adequate prevention system as described. Nonetheless, this topic should be expanded and an analysis of the likelihood of any of the events occurring should be done.

5.5. Space allocated.

The space to be allocated is mainly determined by the size of the components and the security considerations. The ESF in terms of required space is basically formed by the supercapacitor modules and the DC-DC converter.

The space taken by the supercapacitor modules is given in the data sheet of the "SkelGrid 2.0". For 10 modules, the system weight is 550 kg and has a size of 600x600x2200mm. To this size a lateral and superior space should be considered to ensure correct ventilation, and a frontal space reserved to maintenance protocols. Since 45 modules need to be placed 5 units/cubicles of SkelGrid 2.0 would be needed, a initial estimation of the space necessary as a group could be 600x3000x2200 mm. The necessary space between modules for ventilation and other functions should be given by the manufacturer, in any case the total area occupied will likely be slightly larger.

To estimate the space that a dedicated DC-DC converter could take, the model “DPS-500 DC-DC converter” is taken as reference. And it will be assumed that the space needed will be the equivalent to 4 of these smaller DC-DC converters. The size of “DPS-500 DC-DC” is 850x1000x2050mm, that gives a total for the space used for the DC-DC converter of 850x4000x2050mm. A distance maintenance and ventilation distance surrounding the converters should be considered.

5.6. Testing protocols

To ensure that the system is under correct operation and that the performance of the SC group is as agreed with the manufacturer a set of tests need to be run. The testing is performed under a specific set of parameters and equipment, and it is based in three main types of tests. Further detail on what is needed and how to perform the tests can be found in [17][47][21]. The main characterization tests are the following:

- Cyclic voltammetry. It is a dynamic electrochemical method that evaluates general electrochemical capabilities and kinetics [17]. It is based on the evaluation of parameters in charging and discharging cycles at different voltage change rates. The main results come from obtaining CV graphs at different kinematic rates.
- Galvanostatic charge/discharge. Technic to characterize capacitance, power, energy density and the series resistance of a SC. The process is based on a full charge and discharge of the supercapacitor at constant current, measuring the evolution of distinct parameters.
- Electrochemical impedance spectroscopy (IES). This protocol is directed towards analyzing frequency related response. Since in this project the application is not related with AC signals, the information obtained is not relevant for the case studied.

Performing these tests should give enough information to ensure that the SC group has the performance expected now of installation. These tests could be done under maintenance stops to ensure that there is no accelerating aging of the components and that the values obtained by the SC management system about the state of the component is correct.

6. Modeling and simulations

This chapter is divided into two main parts. Section 6.1 describes the modeling process. First the necessary elements to be modelled are described, and after the different subsystems are described more in detail. The second section, Section 6.2, focuses on presenting and explaining the result of the simulations, that will be later discussed in depth in Section 8.3.

In this document details on specific parameters of components are not specified. Both for security reasons and since some of these parameters are approximations and not exacts figures from technical specification files. Due to that fact conclusions from this simulation won´t pretend to do a precise analysis on the exact figures but, it will focus on analyzing the general behavior of the system.

The modeling has been focused on obtaining the ramp down behavior with the solution proposed. The system starts connected to an ideal grid that sets a DC voltage on the intermediate DC grid of 1000V. Once the signal is stable the grid is disconnected, the Supercapacitor connected and the ramp down protocol starts. More detail on the specific systems modeled is given in the following subsections.

6.1. Modeling

In this section the modeling of the most relevant element and systems is presented. Starting with the element modeling, three main elements are presented which are mainly the converters between the DC intermediate line and the rest of the systems. After the systems model is described, the main elements and connections are presented.

6.1.1. Element modeling

As mentioned above, Simulink offers numerous certified and periodically updated libraries where many basic elements for physical systems are modelled. Nonetheless, more complex systems are usually not available and thus the user has to do the modelling work. In this case the AC/DC drive block and the booster block needed to be modelled specifically for this application. As the goal of this project is not coming to a precise model of each particular of these elements (which could be a project in its own), basic electrical description of these elements has been used for its modelling. The mentioned systems are described more in detail below:

- DC/DC booster

The DC/DC booster is the element situated between the Supercapacitor group and the DC intermediate line. It has the function of adapting the variable DC voltage of the Supercapacitor to the desired voltage in the intermediate line. The scheme of the block is shown in Figure 18.

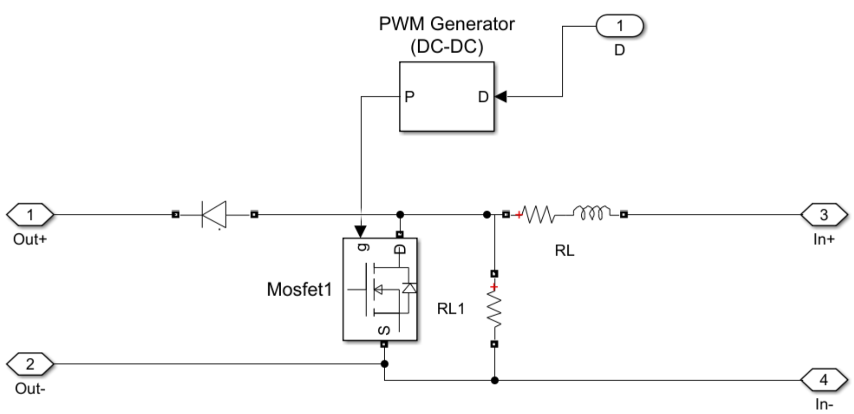

Figure 18. Booster block Simulink Model.

The main two blocks forming the booster is a PWM Generator and a Mosfet. Additionally, an RL block is added to simulate the losses, a resistance of high value in parallel is needed to avoid the discontinuities on the simulation, and a diode are necessary. The ports marked as In are the input ports connected to the supercapacitor. While the ports marked as Out are the connection points to the intermediate line. Finally, entry D is the control output that allows the system to manipulate the voltage set in the DC line.

- DC/AC drive

The DC/AC drive helps to control the power into the HCP motor and transform the signal from DC in the intermediate line to AC in the HCP motor system. The scheme of the block is shown in Figure 19.

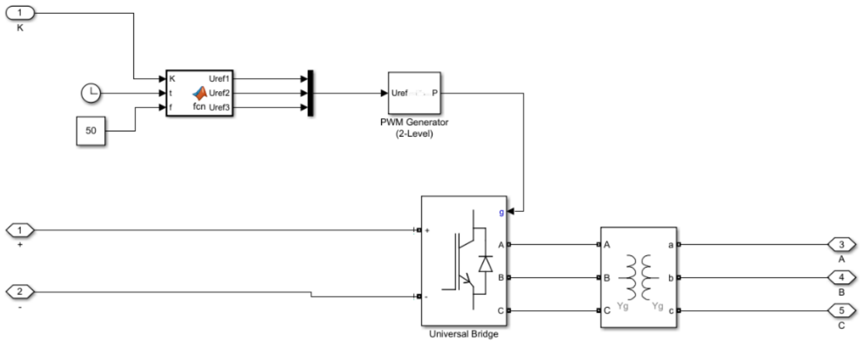

Figure 19. DC/AC Drive block Simulink model.

The drive in this case is built in a similar way to the booster. It has two main blocks: the PWM generator, which generates the signal to control the switching of the diode bridge, and a 3-arm diode bridge that converts the DC signal to a three phase AC signal. Additionally, it uses a MATLAB function that adapts the control signal to generate the adequate PWM signal and a transformer that helps adapt the voltage to the base parameters given in the real system.

6.1.2. System Model

Once all the elements of the system are modeled the general system can be formed. For the sake of clarity, it will be presented in 5 subsystems: The SC group, the HCP system, the ideal power grid, the intermediate DC grid and the control loop. These 5 are presented in detail below:

- Supercapacitor group

The supercapacitor group corresponds to the energy storage system designed in Section 4.3. This group is modelled with the booster block modelled before and using the Supercapacitor block from the Electrical library of MATLAB. The supercapacitor is loaded with the design parameters selected and the booster is configured so the voltage of the intermediate grid is 1000V. The model of this group is shown in Figure 20.

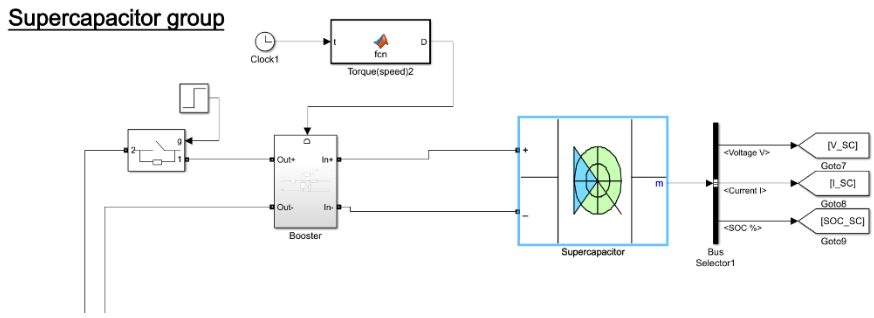

Figure 20. Supercapacitor group Simulink.

Some additional components used is an ideal breaker that will help handle the connection to the intermediate grid and a function that sets the control input for the booster. This decision will be decided in the control loop part. The booster acts as an intermediate system between the ES module and the DC line (as designed in Section 5.1).

- HCP System

The HCP system constitutes the system from the DC/AC drive to the HCP motor. In between the main elements are the group of RL in series and C in parallel representing the frequency filter, a step-up transformer and a resistance that represents the impedance of the line. The model of the HCP system in Simulink can be seen in Figure 21.

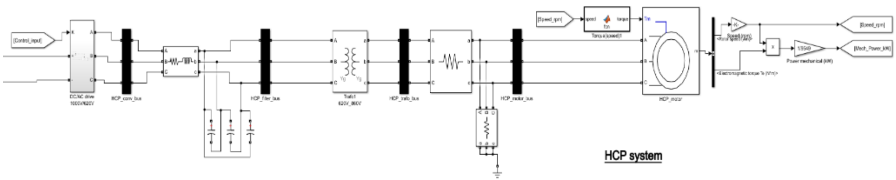

Figure 21. HCP system Simulink.

In Figure 21 other minor components are a resistance in parallel with the HCP motor which allows the system to solve the simulation problem, a torque (speed) function which pretends to emulate the resistance curve of the flow; and a control input that modifies the output voltage of the drive so the speed of the motor follows the desired speed curve.

- Ideal PowerGrid

For the grid side a major simplification has been performed. Since the interest of the simulation lays in the relation ESF to HCP motor during the speed ramp down, the grid just plays a role setting the conditions before the start. Thus, an infinite source with a transformer was enough to represent the whole grid side. That is connected to the intermediate grid with the use of a rectifier that converts the AC voltage to the 1000 DC voltage desired in the intermediate grid. The model used for the ideal grid is presented in Figure 22.

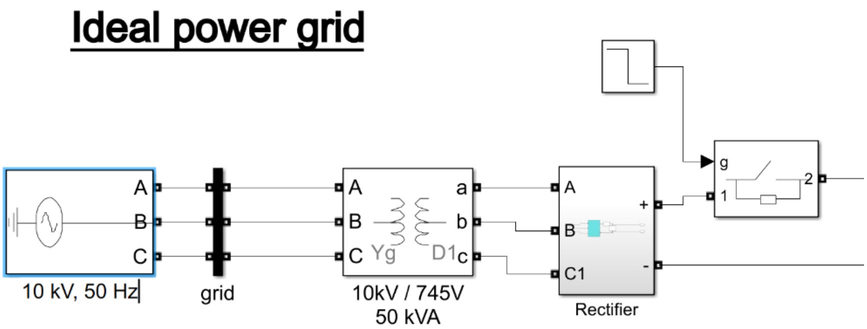

Figure 22. Ideal power grid Simulink.

In Figure 22 the values of the net and the transformer do not correspond to the real values, but they serve as a simplification to set the desired values in the intermediate grid. Additionally, a switch controlled by a step-timed entry is located at the output of the rectifier to disconnect the ideal grid before the ramp down starts.

- Intermediate DC

The intermediate grid has been modeled as an ideal bus where the three big systems are connected: The ideal grid, the HCP system, and the supercapacitor group. There is a supercapacitor in parallel working as a filter for the signal introduced by the switching of the static components.

- Control Loop

The main control loop has been modeled with the use of a PI controller. The system generates a speed reference which is based on the ramp down in Figure 10, and used the measurement of the rotational speed of the motor to calculate the error. The control input generated is used as a control input for the DC/AC drive that actuates on the voltage to affect the speed of the motor. The model of the control loop is presented in Figure 23.

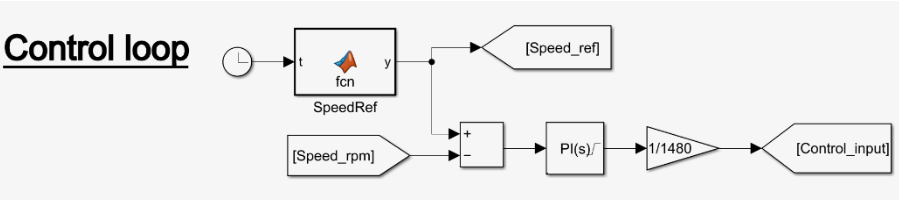

Figure 23. Control loop for speed control. Simulink.

Additional to that control loop it is relevant to mention that the control of the booster step-up ratio, to keep the DC voltage at 1000V, is made with a predetermined function instead that with a control loop. The reasons for this decision and the possible effects of that is be presented in Section 8.3.

6.2. Simulations

Once the model of the system has been introduced it is relevant to set the conditions used for the simulation. The simulation starts from a predefined state: the HCP motor starts with 0 slip ratio; the voltage of the intermedia grid is set to 1000V, and the supercapacitor starts already fully charged. Regarding the state of the breakers, the breaker connecting the external grid is closed (the grid is connected), and the one connecting the SC group is open.

Starting from the initial conditions mentioned the simulation is run for 10 seconds. It is a discrete simulation with a time step of 4e-7s. And it has the following predetermined list of events:

t: 0s – Start of simulation.

t: 0.9s – Connection of SC group.

t: 1s – Disconnection of ideal grid (beginning of ramp down)

t: 1s to 8.88s ramp down protocol

t: 8.88s speed reference to 0 rpm

Since due to the complex setting of the system it cannot be directly initialized with the desired values, and a stabilization time of 1 second is used so the different variables stabilize in the rated values of the system. The time evolution of different values during the simulation have been grouped in two groups: The SC response, the HCP motor. Other values can be measured and plotted but these have been selected because of its relevance to the case.

6.2.1. SC response

The supercapacitor response groups three variables that describe the state of the supercapacitor: the SC voltage, the SC delivered current and the SOC. The response is plotted in Figure 24.

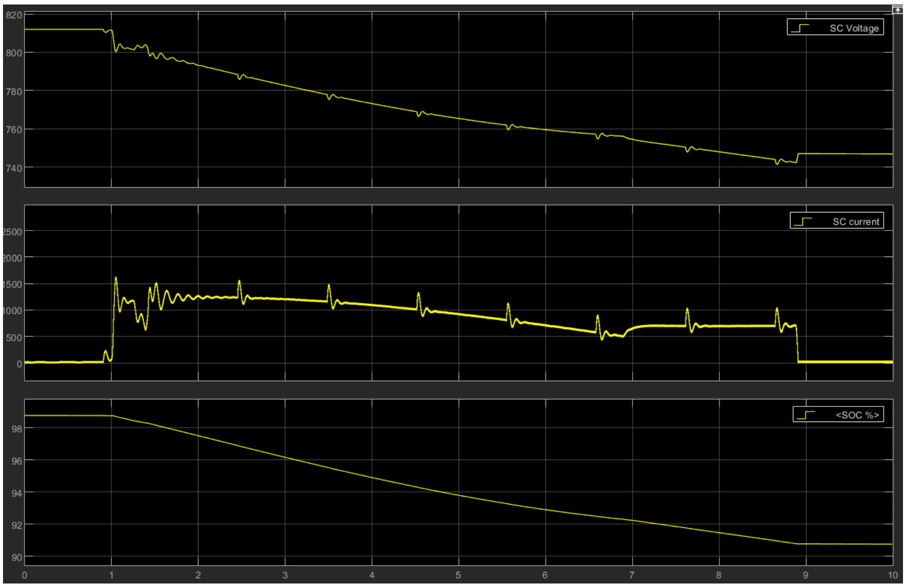

Figure 24. Simulations plots of the SC group.

The voltage starts in 812 V (fully charged) and decreases to a final value of 747V which correspond to a state of charge (SOC) of 90.8 %**.** While the voltage plot presents a smooth output the current presents higher variations. These are discussed further in Section 8.3.

6.2.2. HCP motor

The HCP motor response is grouped in three variables of high interest. The rotational speed, the mechanical power and the control signal into the DC/AC drive. The time response for these values is presented in Figure 25.

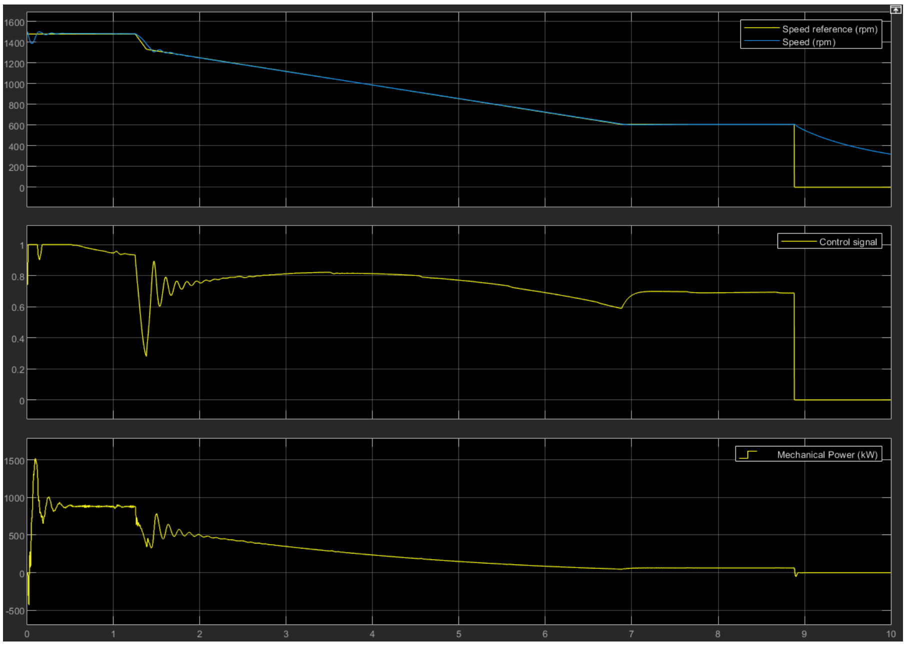

Figure 25. Simulation plots of the HCP group.

In Figure 25 the first plot shows in yellow the speed reference and in blue the rotational speed value, the control signal with a maximum value of 1, and the mechanical power in kW. During the first second the values for speed and mechanical power stabilize and after the first second the control output helps to keep track of the reference. This response is further analyzed in Section 8.3.

7. Economic analysis

The economic analysis of this project is a complex task. Not only data about the price of multiple components is needed, but also information about the engineering related costs, and machinery tests costs would be needed. As it was stated in the goal document, the detail of the economic analysis would depend on the actual data available for it. Up to this point this data is really limited and thus a detailed economic analysis of this solution cannot be expected. Therefore, this section will be used to give some qualitative insight on the different aspects that would need to be considered in case this solution was studied further, to provide some basic guide for future work in the topic.

Starting with the investment in equipment, the system has two major investments to evaluate: the SC group and the DC-DC converter. The rest of the components, including filters, DC cables, information cables or security switches, could have a cost of 5-10% of the total investment in equipment. According to different scientific articles and providers it can be safe to assume a cost of 2500-5000$/kWh ([28][14][18]), leaning towards the lower end of the spectrum. That would mean an investment of 26000-52000 $ for 10,378kWh, that is for the case 4 used for the calculations, see Table 6. Regarding the DC-DC group ranges vary too much to give an accurate estimation but it could range from 100 000 – 300 000 $.

The price for the operators and engineers' work, both for the design and commissioning of the system is impossible to estimate. But it is safe to say that it will take most of the investment dedicated to the project.

Regarding the cost of operation two factors need to be mentioned. First is the cost of energy consumption of keeping the SC charged constantly. SC present a problem of self-discharge which is a strong drawback when the installation wants to be used to store energy in long periods disconnected from the grid due to the loss of capacity overtime. This is not a problem in the function of this project since a source is always available to charge the ESF. But it certainly has some effect in the losses on the system. Self-discharge affects the total losses on the system in a minor way, and thus has some impact (although small) on the operational cost. An estimation is impossible to make at this stage due to the number of possibilities, but it should not be expected to be higher than losses in other major components (transformers, convertors, or filters; for comparison, the self-discharge is most of the times higher than in batteries). As for the operational cost dedicated to maintenance price of maintenance everything points to that under a well sized system with an adequate control, and a robust filter design no considerable maintenance cost should appear [13].

8. Results and discussion

In this section the results of this thesis are evaluated, strengths and weaknesses are mentioned, and decisions and possible effects of those in the results are explained. For that the results will be compared with what was expected theoretically, with tests run in the plant and evaluated by themselves.

The section is divided in the following Subsections: Energy calculations, technical overview, simulations, maintenance, and physical space. These sections constitute the central part of the future project, and it is relevant to discuss the decisions and results obtained, which could be valuable in case the project decides to go forward.

8.1. Energy calculations

The energy and power calculation served as a base for the general sizing of the system. Two approaches were taken to calculate these. The first one is the calculation of the necessary power of the motor for every instant during the ramp down and the calculation of the power necessary at the ESF using the system losses. The other one was more simplistic, it used the theorical calculation of the inertia of the ESM and used its value as valid basing the argument in a test-report performed into the system. Both approaches are analyzed and compared.

The advantage of the first approach, calculating the power necessary at every instant during the ramp down, is getting a power requirement profile. Electrical components do not experiment with the same behavior over different loads, and having the power profile at every element allows for a more precise calculation of the energy required. Not only that, but it can be valuable when contacting a supplier, since with that curve the detailed behavior of the technology needed is described.

In this case, the main drawback of this approach is that the data available for the components was based on rated power operation and assumptions needed to be made regarding the rest of the spectrum. That means that the advantage of having a detailed way to know the necessary energy is partly lost in the validity of the assumptions made.

Regarding the assumptions themselves some are more accurate than others. But in general, a conservative approach was taken when approximations were necessary. This could have influenced the sizing of the ESF, although if there is some effect it should not be highly impactful.

With all of that said the first method gives valid values to serve as a base for the sizing of the components. Afterall the selected components have a considerably bigger size than the minimum values set by this approach. Also having an approximate curve allows for a calculation of expected peak voltages and currents, which are basic for the pre-design of the electrical components and its simulation.

The second method is straightforward and the information that it gives is valuable since it is based in recent tests on the facilities. Nonetheless the information obtained is limited, since only the value of the theoretical energy stored in the ESM is obtained. No information about how much of that energy is delivered, or how it is delivered through time is given. The result of this method is that the current energy storage has $3517{,}5kWs$ available rotational energy and that it is enough to perform the ramp down successfully. As I see it, it serves as a checking value, but it lacks detail to make a SC sizing on its own.

It is noticeable that the energy stored itself is not the decisive factor in the design of the ESF resulting in a total energy stored approximately 6,7 times higher than the energy stored in the current system, (23538,6/3517,5kWs). This is due to the high voltage needed to get a reasonable current in the ESF side and to be able to deliver the peak power required.

In conclusion, the use of the two methods is a great solution. The doubts that could have aroused during the assumptions made in the first method are backed by the trusted value given by the current

ESM. Nonetheless having more detail about the components would always be a good input to get more detail in the power curve obtained.

8.2. Technical overview

The focus of the project is the use of SC as a replacement of the actual ESS. And after studying the technology and the fit with the current application it is reasonable to say that using supercapacitors as a emergency backup system is a technically feasible solution. Not only can it deliver the power required under the most demanding conditions but also relies on commercially tested technology, which will ensure safety and reliability giving the desired performance over the lifespan of design. In addition to that, the solution selected has a high degree of modularity which helps fast maintenance in case it is needed.

Focusing on the actual technical solution adopted, a solution of 810V based on the supercapacitor model SCH3400 has been adopted. It consists of 5 54-cells modules in series, disposed in 9 rows in parallel. Which gives a total of 45 54-cells modules. Compared with the lower voltage solutions it gives a system with a much higher size and lower capacity utilization. Let's first discuss the voltage level of the SC group.

Regarding the decision to select a higher voltage group it has been founded both in the theoretical research and expert insight. Using a voltage closer to the desired DC-DC voltage helps with the design and stability of the DC-DC booster. Additionally, it reduces the current on the ES circuit and helps both selecting a DC-DC drive technology and in the future design of minor components as cables. It is not only that the system is more stable ensuring a higher voltage but that the solution with a lower voltage would lead to values for current that would complicate the design and selection of the rest of the components.

Looking for a higher voltage solution in SC requires of a higher number of supercapacitors in series. This wouldn´t be an inconvenience if the number of parallel branches was reduced in exchange. But due to the method used for the sizing, the result ends up requiring a bigger amount of supercapacitor modules to fulfil the function. That leads to the question of, is the current sizing methodology adequate or is it leading to a unnecessarily oversized system?

With this methodology the solutions that have been obtained in general are highly demanding in a low ESR, which has to do with the methodology being based on saying that the total energy requirement is delivered at peak power. The question is, could a SC group with a higher ESR (less branches in parallel) provide the peak power for a shorter time period? Which based on the SkelGrid technical specifications seems to be possible. For a branch of 5 54-cells modules in parallel, the specification gives a "1s Peak Power (kW)" of 1415 kW. For this case that is approximately the power needed for 0.25s. Even considering that this value is not for EOL conditions and that the main requirement of the system is being safe and reliable it is probable that a solution with less branches in parallel could fulfill the requirements needed. Therefore, the sizing methodology used could have led to a unnecessarily oversized solution and should be revised in future work.

The supercapacitor solution requires a DC-DC drive that adjusts the voltage of the intermediate grid to a desired value. Together with that, in the system there are two other static devices: the DC-AC drive of the HCP system and the AC-DC converter of the general grid. The switching nature of this behaviors of these components introduce complex frequency behaviors that have to be specially considered.

The harmonics analysis of the system is out of the scope of this pre-study. Nonetheless, studying the switching frequencies and designing adequate filters to diminish the effect on the system is a major point for system stability. Instabilities that can lead to major fluctuations in voltage or current can compromise the state of major components and is the main threat to safety of the SC group.

8.3. Simulations

The goal of simulating the system is both to observe if the energy calculations are on the range expected and if there are other electrical or control related behaviors that should be considered in a detailed system design.

The SC behavior shown in Section 6.2.1 give information about the SC voltage and current overtime. The results shown and the energy calculations made for the SC group are approximately in the same range. The simulations give a final voltage of 747V with almost a 91%SOC, while the result from the simulation gives a slightly lower discharge with a final voltage of 759V. Thus, both results indicate that the group of SC selected has more than enough energy to cover the demand during the ramp down.

The discrepancy between both values is expected and is mainly due to two causes. Both causes come from the assumptions made when selecting parameters of the different components. Not having the precise parameters, first to calculate the losses during the energy balance process, and for the modeling of the system lead to discrepancies. Discrepancies both with the real situation but also between results. In case a more detailed assessment expects to be done it is important to get accurate data for the components over all the range of operating values and avoid assumptions and approximations.

In the same Section, the Figure 20 presents the current values given by the SC. Which can be seen mainly in swings in the SC current. Problems with the frequency response are also observed in the intermediate voltage of the DC line, see Figure 26. That points again to the importance of a detailed design of filters to avoid these fluctuations.

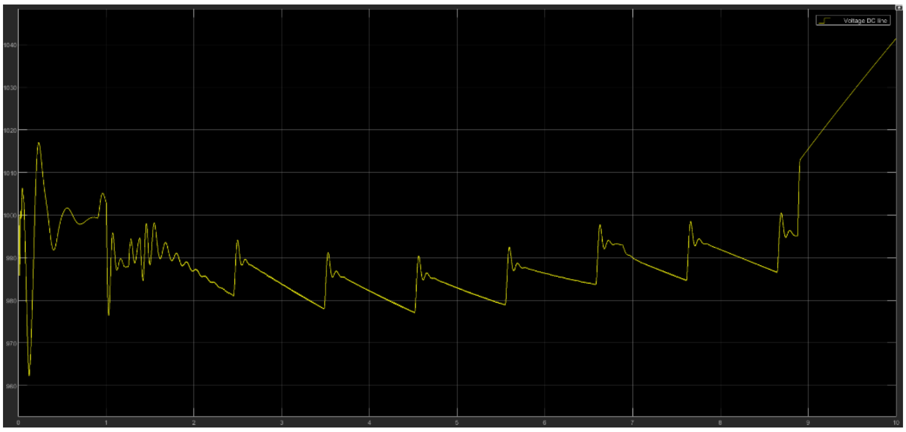

Figure 26. Simulation of voltage in the DC line.

Regarding the values for the HCP motor system behavior are highly satisfactory, see Figure 25. The speed reference is followed satisfactorily over the whole range of values and the ramp down in power of the motor is made without major complications. The two main components are used to control the system, these are the DC-DC booster and the DC-AC drive. In this project the control of both has been implemented in a simple way which is far from what is expected in reality. For the DC-AC drive a PI controller is used, while the DC-DC booster is controlled by a pre-set parameter following a pattern. This approach was taken due to two reasons. First, this being a pre-study, it does not make sense to get into detailed control system design. And lacking a good filter design made even more complicated the design of a fast-response effective control system.

While the result on following the speed is satisfactory it could be improved in the first two seconds of simulation, where after the first ramp down the system fails to follow accurately the reference, as it is seen in Figure 27.

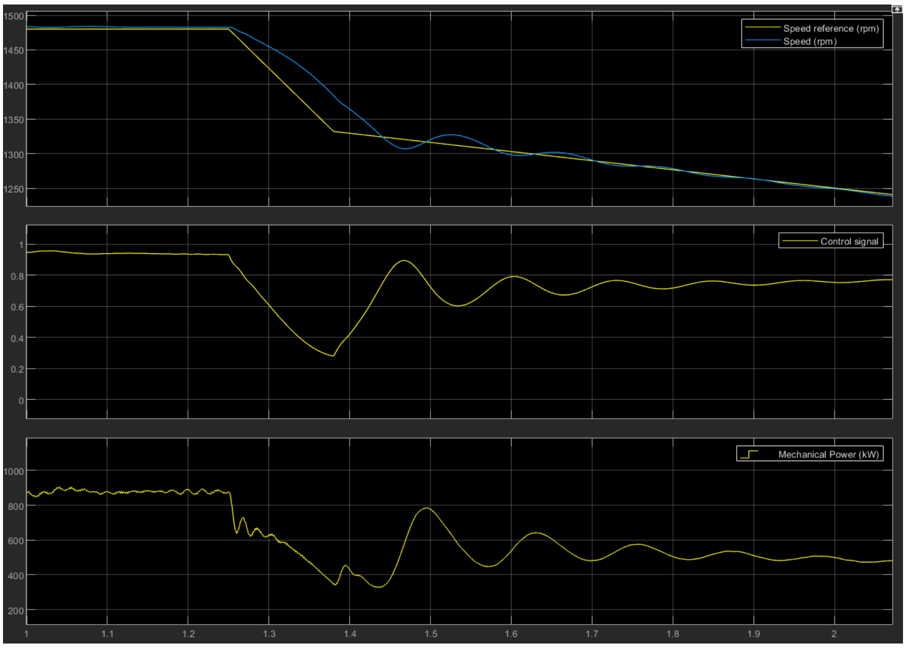

Figure 27. 1s HCP group plots, Simulink.

Being the ramp down of the system a “known” response strategies with implementation of predictive control could give really accurate results for achieving the desired response.

On the other side, the control implemented in the booster to keep the DC voltage at 1000V DC has not achieved the desired results. The main reason is that the implementation of a control system was highly influenced by instability and led to fluctuating responses, thus a simpler solution based on an independent parameter had to be implemented. The voltage of the DC intermediate line is present in Figure 26.

The intermediate grid voltage presents fluctuations that makes it difficult to get a better control strategy. This is most likely related with frequency related issues mentioned.

Overall, the results obtained in the simulation of the process give valuable insight on the process, nonetheless it cannot be used as a precise simulation model to predict exact behaviors in the plant. For that improvements in the parameters, filtering and control would need to be made.

8.4. Maintenance & Safety

Regarding system maintenance and safety indicate the importance of a deep frequency analysis and sizing of the SC group. Following those two principles all the literature reviewed indicates to the fact that no major issue should appear in that matter.

An important parameter is the tracking of the internal measurements of the SC modules. Selecting solutions with internal life and state monitoring helps to keep the system already under good operation conditions. In addition to that performing the tests indicated in Section 5.6 can help, both to ensure that the performance parameters given by supplier are fulfilled before installation, and to analyze the state of the system periodically (ex. Every 3 years). Regarding the technology selected, it is also positive that in case of any issue or error in one of the supercapacitor modules it is easy to replace due to the high modularity.

The main problem with the methods given regarding maintenance and safety in Section 5.4 is that they are not case specific. In these cases, most of the information about the system maintenance and safety comes from tender information. So, in this aspect accentuate the importance of stating implicitly all the requirements for the system when contacting a supplier, both regarding performance and regarding security. And get most of the information about this topic for the designed order.

8.5. Physical space

The physical space is highly dependent on the technical equipment selected and the safety measures that should be considered. As mentioned in Section 8.2 the option selected for the supercapacitor group is probably considerably oversized. That has led to the need for 5 cabinets of supercapacitors modules. Considering other sizing methodologies and getting detailed insight from the supplier about the capabilities of a particular technology could reduce the need of cabinets to 2-3, reducing the space requirements in half.

The same conclusion is reached with the DC-DC booster. There solutions found are thought of for outdoors installations of photovoltaic modules. Contact with different suppliers can lead to smaller equipment in the final installation.

9. Conclusions

The goal of this project was acting as a pre-study to assess the feasibility of a Supercapacitor group to replace the ESF that acts as a security back-up for the HCP in OKG nuclear plant. As a result of the project, it can be said that from the technology standpoint using a SC group for this task ensures good performance and high reliability over a long period of time.

The SC technology lends itself perfectly to the application requirements: high power and relatively low energy stored. It admits high cyclability ensuring adequate performance during the lifetime expected. And the physical space necessary for its installation if reasonable and should not impose a limitation for its application. When the sizing of the final component needs to be done a balance between security and economy should be done. Going for high values of voltage for the group appears to be beneficial from the security and performance standpoint, although a deeper analysis should be performed to avoid the oversizing of the group. Also considering end of life parameters is crucial for correct sizing.

The connection to the already available system through a DC-DC converter is adequate from the technical standpoint. As mentioned, it is highly important to design adequate filters to avoid resonance effects due to the switching nature of different components. Apart from that for the design of the DC-DC technology the main parameters to consider are the peak power, the control needs, and the voltage levels, which are imposed by the SC and the system.

The main control systems to be designed/adapted are the ones controlling the voltage of the intermediate grid and the power delivered to the HCP motor. Robust designs that avoid the influence of resonances with the system should be prioritized. Additionally, an adequate control mechanism for the charging of the ESF should be considered; SC are sensible to high charging currents and that can lead to internal failure.

Regarding security and maintenance no major inconvenience should be expected. All the technology considered is industry tested and highly secure. The main area to control is the physical security of the systems and the protection against electrical resonances.

This document presents the general bases and guidelines to consider when approaching this work. Details on the operational and investment costs for the project have not been found, but some guidelines have been given and can serve as a rough base to compare with other similar technologies. To conclude, note the importance of the collaboration with suppliers and manufacturers of the technologies selected and the setup of performance parameters to be fulfilled by the equipment selected.

10. Future work

This project is based on a specific requirement of a storage system for the OKG 3 nuclear reactor. Therefore, most of the future work relies on analyzing other solutions that are industry-proven and that could fit adequately with the required characteristics of the system. In case this solution is considered the most suitable one, or it wants to be studied further to analyze more in detail the impact on the plant, many areas could be object of future work.

Regarding other solutions that could be analyzed, keeping the energy storage motor (ESM) is one possible solution that needs be considered. Assuming that was the case, studies of the current state of the motor should be performed since it would mean expanding the expected life in at least 20 years, this is especially difficult due to the lifetime of the power electronics of the ESS. Analyzing the maintenance possibilities of the gears together with an analysis of costs could be an area to explore, with the objective of expanding the lifetime of these and reducing the costs associated. Considering other bearing technologies is also an interesting field of study, that if successful could be one of the bests solutions, since it would not need to replace the whole system and just the bearing system. Exploring magnetic bearing or “floating” bearings could be a possibility.

Exploring other technical substitutes of supercapacitors could also be an interesting direction. Although due to the application characteristics supercapacitors seem to be the most suitable technology, the development of Li-on based batteries between other could offer similar if not better characteristics. Taking as a base the energy requirement calculations, this should not be too time consuming.

If the decision to develop the project further is taken, there are many areas where future work could be directed towards. Some of the technical related ones are listed here, but a lot of tasks that have to do with documentation, testing, simulations, and security would also need to be added if the project is finally carried out.

- Reviewing the sizing methodology for SCs used, validate and evaluate whether it leads to an unnecessary oversized system or not.
- Develop a new control structure. The modifications that would need to be made to carry out the new solution would affect the complete control strategy that is currently in place. Considerations should be taken both in the new DC-DC driver, and all the other elements involved in the ramp-down strategy. As the HCP driver, and also the control for the rectifier coming from the outside grid.
- Charge-Discharge strategies. Although the discharge strategy is limited by the power required, the charging of the supercapacitors has multiple possibilities. Charging and discharging speed have a big influence in the lifetime and performance of the supercapacitors so it should be studied in more detail. Analyzing the problem of self-discharge and how to tackle it.
- Space allocation and dedicated cooling. A project for both the space to locate the supercapacitors and a dedicated cooling system for them should be specifically considered.
- Detailed economical assessment. As in any engineering project a detailed assessment of the economic impact of the new solution should be included.

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