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Assessment of Using Superconducting Magnetic Energy Storage for Current Harmonic Compensation

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Assessment of Using Superconducting Magnetic Energy Storage for Current Harmonic Compensation

To my family and friends,
"Everybody is a genius. But if you judge a fish by its ability
to climb a tree, it will live its whole life believing that it is
stupid.- Albert Einstein

Abstract

This thesis was developed in the frame of the increasing need for power quality control due to the presence of non-linear loads connected to the grid that inject undesired harmonics. The absence of research regarding the simulation of Superconducting Magnetic Energy Storage technology in this type of application made it an interesting approach to study and develop, with the additional benefit of creating an open-source project to catalyze further research. This harmonic correction was achieved by using an active filter composed of a voltage source converter, a capacitor, and a Superconducting Magnetic Energy Storage unit. Using Superconducting Magnetic Energy Storage technology allows the use of this type of system in renewable generation, more specifically wind farms, reducing production variation and ensuring an increased power quality of the electrical grid. This work exhibits a positive result of using Superconducting Magnetic Energy Storage technology on harmonic correction and catalyzes further simulation research and possibly a practical application derived from this work's developments and provided tools.

Keywords: Superconducting Magnetic Energy Storage, Active Filter, Power Electronics, Voltage Source Converter, Non-linear load, Wind farm, Simulink Simulation

Resumo

Esta tese foi desenvolvida no contexto do aumento de cargas não lineares conectadas à rede que injetam harmónicas indesejadas e a consequente necessidade de controlo de qualidade da energia fornecida. A ausência de material de estudo relativo à simulação da tecnologia de armazenamento de energia em bobinas supercondutoras neste tipo de aplicação foi interessante para o estudo e desenvolvimento, com o benefício adicional de criar um projeto para catalisar novos desenvolvimentos. Esta correção de harmónicas foi obtida por meio de um filtro ativo composto por um conversor baseado numa fonte de tensão, um condensador e uma unidade de bobinas supercondutoras. O uso de tecnologia de armazenamento de energia em bobinas supercondutoras permite a utilização deste tipo de sistemas em fontes de energia renovável, mais especificamente em parques eólicos, atenuando as variações na produção e garantindo a qualidade de energia da rede elétrica. Deste trabalho resulta um resultado positivo do uso da tecnologia de armazenamento de energia em bobinas supercondutoras na correção de harmónicas e catalisa novas pesquisas de simulação e, possivelmente, uma aplicação prática que tenha como base os desenvolvimentos deste trabalho e das ferramentas fornecidas.

Palavras-chave: Bobinas supercondutoras, Fitro activo, Electrónica de potência, Conversor de tensão, Carga não-linear, Geração eólica, Simulação Simulink

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Acronyms

AC Alternating Current

AF Active Filter

AM Amplitude Modulation

BESS Battery Energy System

CSC Current Source Converter

DC Direct Current

FFT Fast Fourier Transform

HTS High Temperature Superconductor

IEEE Institute of Electrical and Electronic Engineers

IGBT Insulated-Gate Bipolar Transistor

LTS Low Temperature Superconductor

PCC Point of common coupling

PCS Power Conditioning System

RMS Root Mean Square

SMES Superconductive Magnetic Energy Storage

STD Standard

THD Total Harmonic Distortion

VSC Voltage Source Converter

CHAPTER 1

Introduction

1.1 An introduction to SMES

Renewable energy sources such as solar and wind are showing progress in reducing the human impact on the environment caused by the rate that energy consumption is increasing over the years.[1]. Today's energy quality standards are at an all-time high; many grid users, for example, data centers, need to have a very stable energy input without any interruptions, voltage drops, or unwanted harmonics.

With the development of power electronics, it has never been easier to convert energy; cheaper and more efficient equipment creates opportunities for technologies that have not been viable until now. SMES (Superconducting Magnetic Energy Storage) is used in very few applications due to its high initial investment and passive energy consumption. However, thanks to recent developments in HTS (High-Temperature Superconductors), a bright future is beginning to take shape.

This work's primary focus is in power electronic controllers applied to SMES technology, more specifically, to remove all unwanted harmonics of a wind farm and all the information present in state of the art was the best found about the subject in question.

1.2 Motivation

The proliferation of harmonics was one of the foundations in choosing this thesis's subject, combined with electrical superconductivity which is an exciting physical phenomenon that has some very interesting properties, exploring this combination was the central objective. Initially, the goal was to create a practical SMES installation and connect it to the college's wind turbine present on the roof of one of the buildings, which due to the varying wind speeds, produces low-quality energy due to a high number of harmonics, but this was quickly dropped due to costs. Nevertheless, it is exciting to work with a unique technology like SMES to reduce harmonics, and possibly in the future apply it to renewable energy sources, widening the path for a sustainable future.

1.3 Objectives

As referenced previously, this work's primary purpose is to reduce the current harmonics caused by renewable generation, more specifically, wind farms; in order to achieve this goal, research is needed to create a possible solution for the problem; having this in mind, it can also be theorize that it might be possible to expand this correction for more scenarios in regards to power quality. As per the reasons exposed in the motivation section, the primary energy storage component will be a SMES system; it would be desirable to have the lowest total harmonic distortion (THD) possible, and that will be a common goal moving forward. Even today, this harmonic removal is already used because high levels of harmonics can cause some erratic behavior of electronics; even if subtle, overtime effect can compound and cascade into a more severe problem. The main goal will be to correct common configurations, such as a grid supplying a non-linear load and a wind farm supplying a non-linear load. This work also aims to create a simulation platform that can be used in future research, catalyzing research and work on the subject, with this in mind, all the code developed in this thesis will be available for public use.

CHAPTER 2

State of the art

2.1 Superconducting Magnetic Energy Storage

2.1.1 Introduction

There are various energy storage solutions such as battery energy storage systems (BESS), pumped hydroelectric storage systems, superconducting magnetic energy storage (SMES) systems, and super-capacitor systems. Each of these technologies has its upsides and downsides; for example, BESS has high energy density and low power output when compared to SMES systems and super-capacitor systems. The comparison between different technologies is displayed in figure 2.1. SMES systems store electrical energy in the form of a magnetic field created by a direct current; this current runs through a superconducting coil that has negligible resistance causing the losses due to the joule effect to be virtually zero.[2] The power conditioning system (PCS) in SMES systems controls the energy transfer between the grid and the superconducting coil; these PCS can have different topologies based on the SMES system's application. Applications that need active power control thyristor-based SMES can be used, if the need is reactive power or both active and reactive power, voltage source converters (VSC) or current source converters (CSC) based SMES is required.[3] The coil on a SMES system is made with superconductive tape that has superconductive properties at low temperatures; the superconductive tapes can be divided into two types, High-Temperature Superconductor (HTS) and Low-Temperature Superconductor (LTS). The advantage that HTS has over LTS is the lower power consumption due to the higher operating temperature of these materials. Good results have been achieved at liquid-nitrogen temperatures (around 77 K).[4]

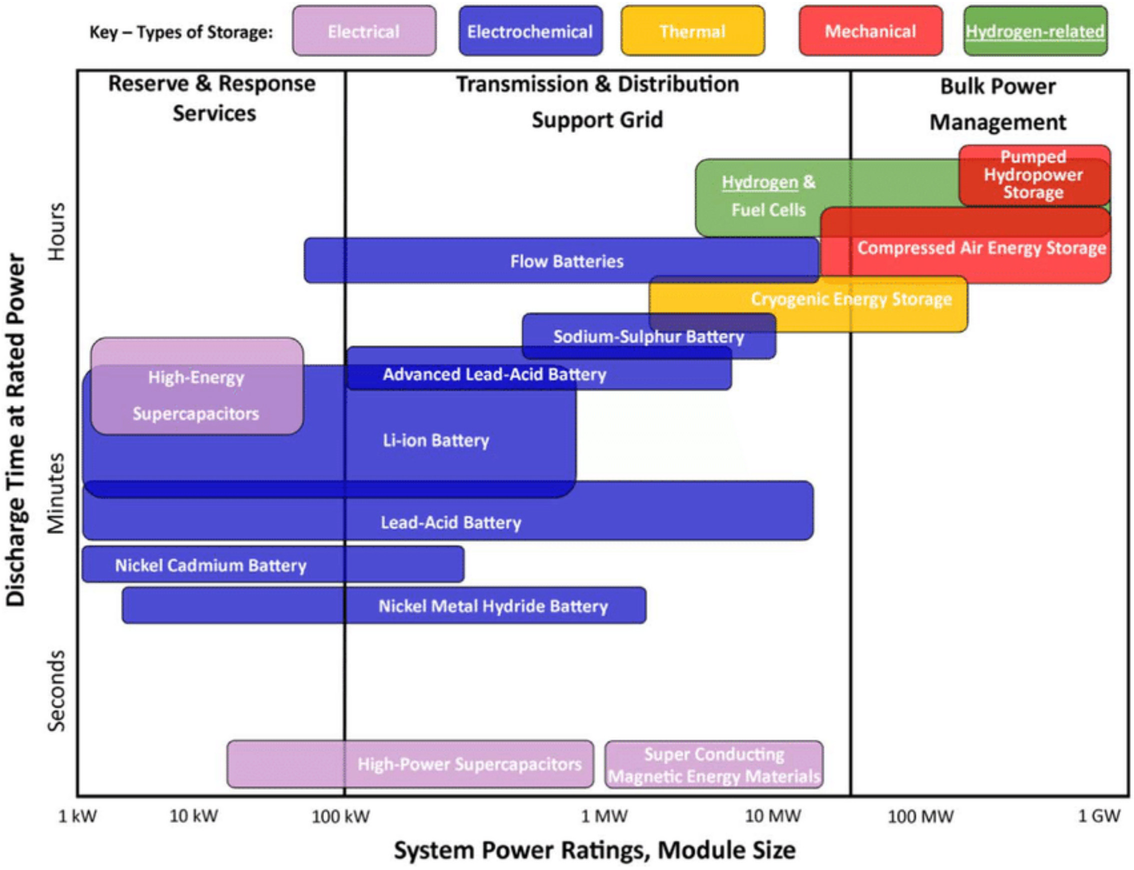

Figure 2.1: Comparison of existing energy storage technologies
Source: Hydrogen - A sustainable energy carrier (ResearchGate - 2017)[5]

2.1.2 Overview

The SMES system is composed of the components described below; a visual representation of a simplified SMES system can be observed in Fig. 2.2.

Superconducting coil Made out of a material with superconducting properties at cryogenic temperatures, in the case of HTS, the coil achieves this state at around 77K reducing the coil's ohmic resistance to negligible values.

Cooling unit Cools and maintains the coolant at cryogenic temperatures.

Driving circuit It is used to control the coil (charging, discharging, and persistent), composed of a DC/DC converter and DC/AC converter. Also, there is a protection circuit in case of a failure when the coil loses superconductivity; if these failures are not handled properly, they can damage the coil.

2.1.3 Characteristics

SMES systems are unique in the sense that they have a lot of beneficial characteristics, high efficiency (charge-discharge efficiency over 95), high power density with fast response

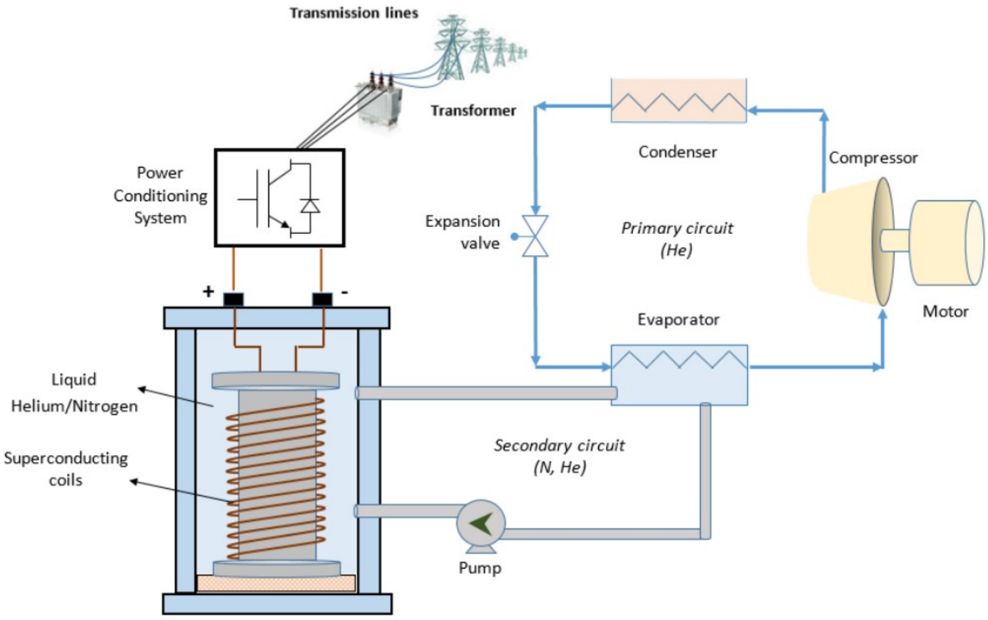

Figure 2.2: Scheme of a SMES system
Source: A comparative review of electrical energy storage systems for better sustainability (2017) [6]

(under 100 ms), long life cycle due to an unlimited number of charging and discharging cycles that can be carried out. [3, 7] To cover the weak points of SMES systems a hybrid SMES-BESS system could be a interesting solution that could yield positive results.

2.2 Total Harmonic Distortion

According to research, there are two definitions of the total harmonic distortion; one states that the THD should be in comparison to the fundamental frequency, the other that the comparison should be made with the signal's root mean square (RMS); this is ambiguous and can cause the misinterpretation of the data [8]. Since it is more useful to use the first definition (and it is recommended to use the first definition in power systems[8]), all the work's total harmonic distortion references will consider the first definition.

Due to power quality standards, the THD definition is getting more used; this method is mainly used to quantify harmonics in voltage or current waveforms. By definition the THD is the following:

$$CurrentTHD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \tag{2.1}$$

$$VoltageTHD = \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \tag{2.2}$$

where I_n is the RMS current amplitude of the n_{th} harmonic and V_n is the RMS voltage amplitude of the n_{th} harmonic, I_1 and V_1 (n = 1) are the fundamental frequency RMS values of both current and voltage, respectively.

2.2.1 Harmonics Removal

Harmonics affect the quality of supplied energy; this is important since there are currently many sensitive consumer loads. Passive or active filters can be used to remove current harmonics from the grid; passive filters focus on creating a low impedance path for high-frequency current harmonics; they are dependent on system impedance, which depends on loads and network configuration.[9] Active filters work by injecting current harmonics to the line current canceling the harmonic content. Visualizing harmonics can be achieved using the Fourier Transform, which is the traditional way of quantifying a signal's harmonic components. Since I will be using real-time analysis of a signal, the Discrete Fourier Transform will be a powerful tool to visualize and quantify harmonics, which uses a limited set of input data values and gives each harmonic component's magnitude.[10] I pretend to remove all harmonic components and keep the fundamental frequency of 50Hz; the Fast Fourier Transform (FFT) is a quick way to compute the Fourier Transform of a signal. While searching for information on the subject, I found a couple of solutions to this problem; for example, active harmonic filtering using VSC was referenced as a possible architecture; this referenced architecture can be seen in figure 2.3.

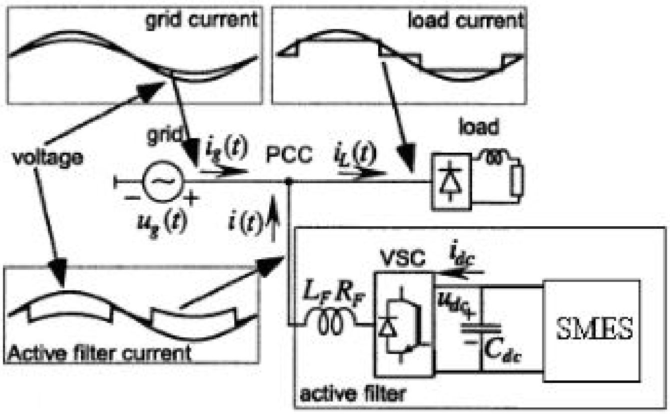

Figure 2.3: Active filtering using VSC
Source: Effect of SMES on Power Quality Improvement (2006)[9]

This architecture seems to be the most simple and thus easy to implement; having few components can also affect the overall cost of a SMES active filter install, which is also a valid point to consider when picking the desired architecture. The separation of the capacitor and the SMES coil by a control system (buck/boost converter) gives an additional degree of freedom when controlling the active filter, which is also a strength of this architecture.

2.2.2 IEEE Standard

The Institute of Electrical and Electronic Engineers (IEEE) is a professional organization, and it is the largest in the world of its kind; this organization aims to benefit humanity by advancing technology. Due to its size and recognition, its standards are widely accepted. While researching I came across standards regarding THD in table 2.1 and table 2.2:

Table 2.1: Voltage distortion limits (IEEE STD 519-1992) Source: IEEE Standards Association [11]

Bus voltage V at PCC	Total harmonic distortion THD (%)
$69kV \leq V$	5.0
$69kV < V \leq 161kV$	2.5
$161kV < V$	1.5

Table 2.2: Voltage distortion limits (IEEE STD 519-2014) Source: IEEE Standards Association [11]

Bus voltage V at PCC	Total harmonic distortion THD (%)
$V \leq 1.0kV$	8.0
$1kV < V \leq 69kV$	5.0
$69kV < V \leq 161kV$	2.5
$161kV < V$	1.5

The tables above show standardized guidelines to control the amount of harmonics present in a grid's voltage; the THD limit by percentage is inversely proportional to the voltage; this means that in high-voltage power lines, the control of harmonics is more strict.

2.2.3 Real life implementations

The following subsection is dedicated to the importance of this work and the role of harmonic mitigation in real-world environments. There are not many manufacturers that supply active filtering solutions, Schneider Electric is one of the few companies that do, and they have installed a couple of systems in the past; The following are some examples of installed energy quality systems and some of the reasons that led costumer to acquire the equipment.[**Studies2014**]:

International Oil and Gas Costumer - Canada The need to meet IEEE 519-2014 harmonic standards.

International Food and Beverage Costumer - Indonesia Power loss mitigation and complying with Korea's regulation of 5% harmonics.

Led Display Manufacturing Plant - South Korea Complying with Korean regulation of 5% harmonics, power mitigation and improving power factor.

Cloud Farms for OS Software Costumer(Data Center) - United States of America Need to meet the IEEE 519-2014 harmonic standards.

Besides harmonic mitigation these installed systems are also capable of power factor correction and load balancing making them a good long term investment.

2.3 Modeling of the SMES Coil

The energy stored in a SMES system can be expressed by following: [12]

$$E = \frac{1}{2}LI^2 \tag{2.3}$$

Where I is the direct current flowing through the coil, and L is the coil's inductance. There are various methods available to determine the coil's characteristics, such as creating a mathematical model, measuring directly, and determining the voltage distribution and frequency response through computer-aided analysis. A mathematical model is a cheap and convenient way to model a system. Some applications might require a more detailed model of the coil; this means that the model can range from a single inductance (which is a rough approximation, enough in most studied cases), a model of the winding like in the one represented in figure 2.4 or even a detailed model that would require the representation of single turns (very difficult to obtain and handle, impractical in most cases).

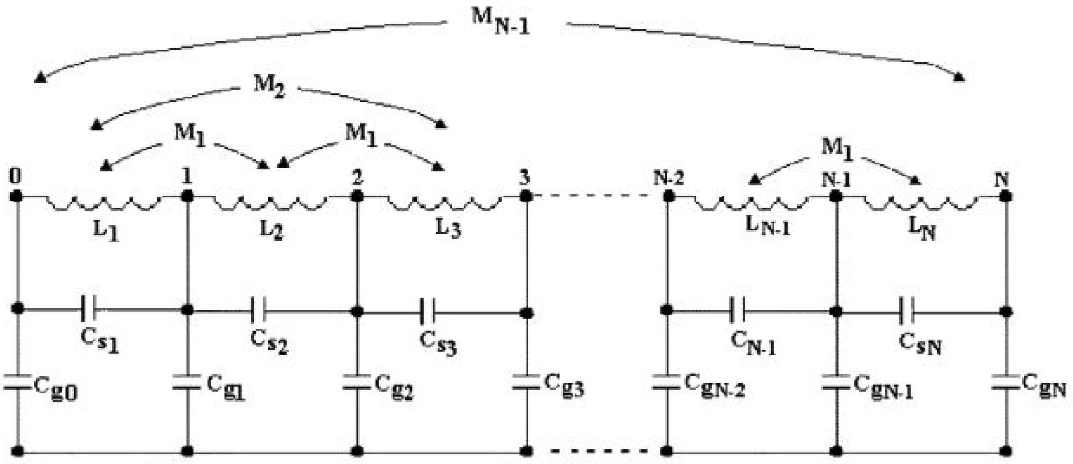

Figure 2.4: Schematic representation of the coil
Source: Detailed modeling of SMES system (2006)[12]

2.4 Electronic filters

2.4.1 Passive filters

In the past, passive-filters were the only known solution in the power quality field, more specifically, removal of unwanted harmonics. This type of filter is composed of capacitors, inductors, and resistors, and they do not need external control or power to perform their function; they are, for this reason, considered passive electrical components. Passive filters are used to enhance the grid's power quality by removing unwanted harmonics caused by non-linear loads and may be split into four different categories:

Low-pass Allow lower frequencies to pass through, attenuating higher frequencies.

High-pass Allow higher frequencies to pass through, attenuating lower frequencies.

Band-pass Allow a certain interval of frequencies to pass through, rejecting the remaining frequencies.

Band-reject Rejects a certain interval of frequencies from passing through.

Passive filters have some issues associated with them; mainly, they are strongly affected by the system's impedance, which creates resonances that amplify harmonics at specific frequencies. Another problem of passive filters is associated with the current rating of the components used; both fundamental and harmonics currents are flowing through them. [13]

2.4.2 Active filters

With the development of power electronics, active-filters became a possible and established solution for power quality problems; this evolution was catalyzed by the many undesired properties of the previously mentioned technology .Active filters need to be configured for each specific system and application, this in turn increases their cost and technical complexity.

The common method to configure a active-filter is composed by three steps [13]:

1. **Converter selection**: Choosing between Current Source Converter (CSC) and Voltage Source Converter (VSC); inductors are usually used on a CSC and capacitors on a VSC. VSC is usually more broadly used due to easier implementation, less monetary cost, and more straightforward control than CSC.

2. **Topology selection**: Choosing between series, shunt and hybrid connection topology.

3. **Controller selection**: Choosing which controller and switching mode is more suitable for the application.

2.4.2.1 Topologies

The previously mentioned topology selection takes into account the following three topologies: shunt, series and hybrid. The most common topology is the shunt topology displayed on Fig.2.5, this type of filters are proposed as a mean of removing current harmonics [14]. The active filter is connected near polluting loads in parallel with the grid and load circuit, this topology samples the load signal and injects an equal but opposite waveform of the harmonics present; these, in turn, cancel out, and only the fundamental component remains. This sampling and injecting of signals requires a more complex control when comparing with passive filter that only need to designed with the system in mind. Shunt filters are usually based on VSC with a capacitor on the dc side and the control is usually made using PWM. The capacitor's voltage is also kept constant by the controller and this is taking into account when the currents that need to be injected by the active filter are calculated.

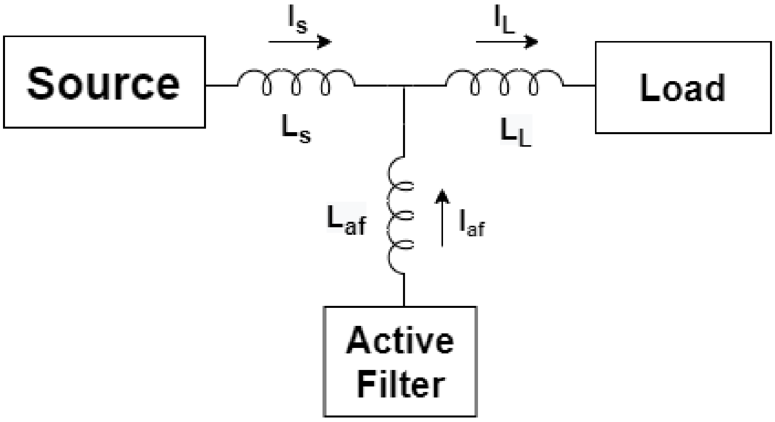

Figure 2.5: Active filter shunt topology

Series active filters, Fig.2.6,were created with the purpose of voltage regulation, stopping harmonics from propagating to the load; in many ways it is similar to the shunt topology, injecting a voltage component in series with the source voltage in order to remove unwanted harmonics or even voltage sags.

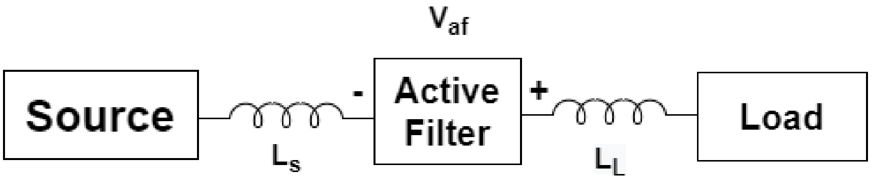

Figure 2.6: Active filter series topology

Hybrid active filters, Fig.2.7,are a combination of both active filters and passive filters, drawbacks of passive filters are compensated by the active filter, this hybrid solution results in a reduced cost and size of the final system, but increases the technical complexity of the filter.

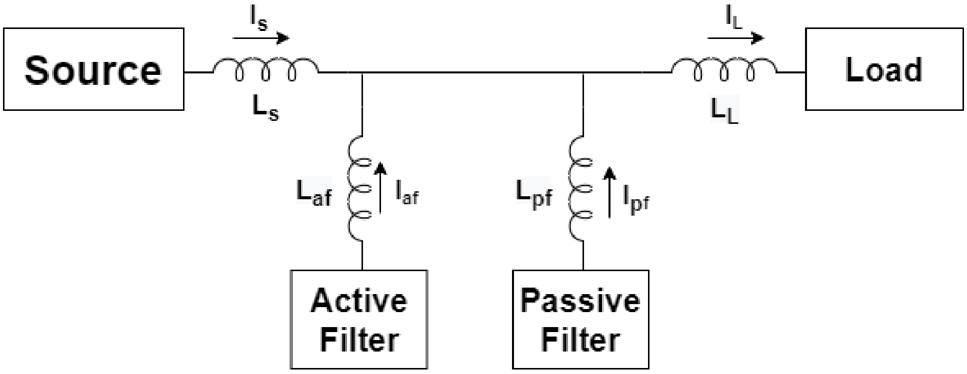

Figure 2.7: Active filter hybrid topology

2.4.2.2 Synchronous Reference Frame Method

In literature one of the most common active filter control methods is the Synchronous Reference Frame Method (SRF); in this method the load current signals are transformed and placed on rotating reference frame with constant angular velocity, this transformation, makes the fundamental currents of the dq components constant, and all harmonic components would appear like a disturbance in the constant dc value [14]. This characteritics are very convinient when trying to mitigate current harmonics, Fig. 2.8 shows a diagram of the previously explained method.

The transformation to $d-q$ can be obtained through the $\alpha-\beta$, after applying Clarke's transform and second transformation is applied, Park's transform, that places the coordinates into a rotating frame of reference.

$$\begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos(\gamma) & cos(\gamma - \frac{2\pi}{3}) & cos(\gamma - \frac{4\pi}{3}) \\ -sin(\gamma) & -sin(\gamma - \frac{2\pi}{3}) & -sin(\gamma - \frac{4\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{2.4}$$

The value γ is a angle that varies with time that represents the angular postion of the reference frame, this frame rotates at constant speed in synchronism with the three-phas ac voltages [15] [14].

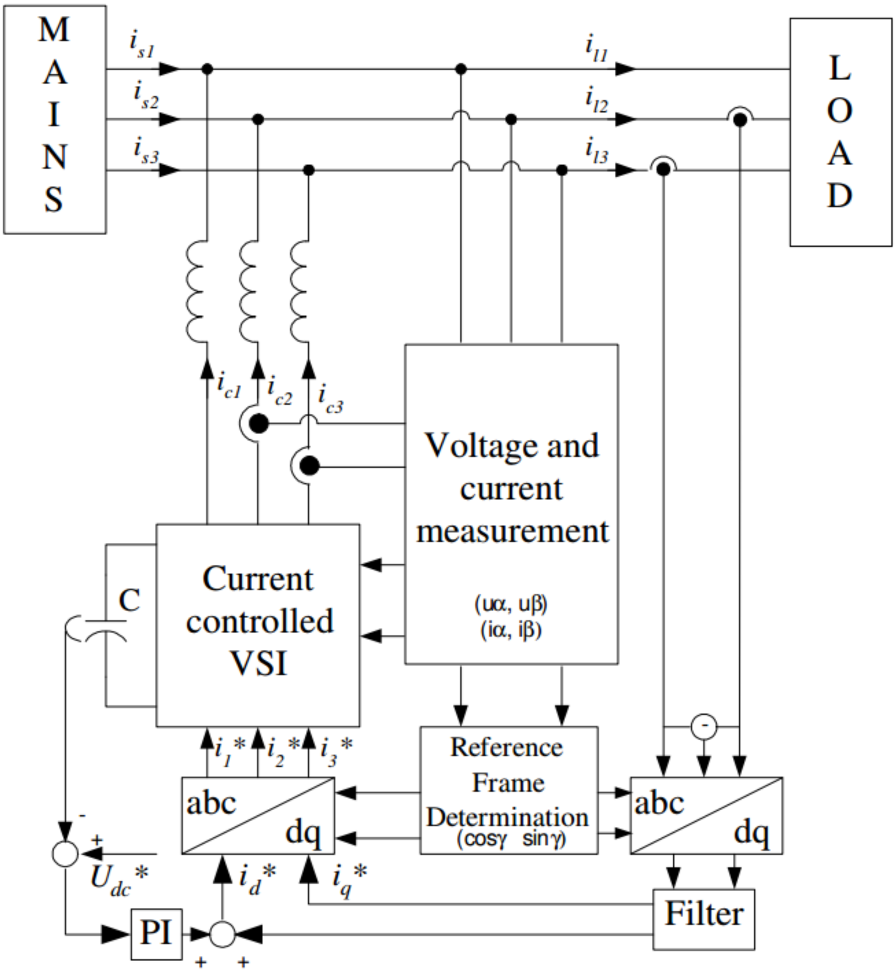

Figure 2.8: Synchronous Reference Frame Method [14]

CHAPTER 3

Active filter with SMES

3.1 Introduction and objectives

This thesis aims to create a solution to remove current harmonics from the grid using a shunt active filter containing a SMES uniquely with the role of energy storage. After researching literature to achieve the presented objectives, an outline of the needed work was created; this outline contained a solution that collected real-time data of a generator and calculates the most significant harmonics using the fast Fourier transform (FFT), implementing a power conditioning system (PCS) architecture that suits the needs and creating a control method to control the SMES system, injecting current to the line and mitigating harmonics; diagrams were created and are present in Fig.3.1 and Fig. Fig.3.2.

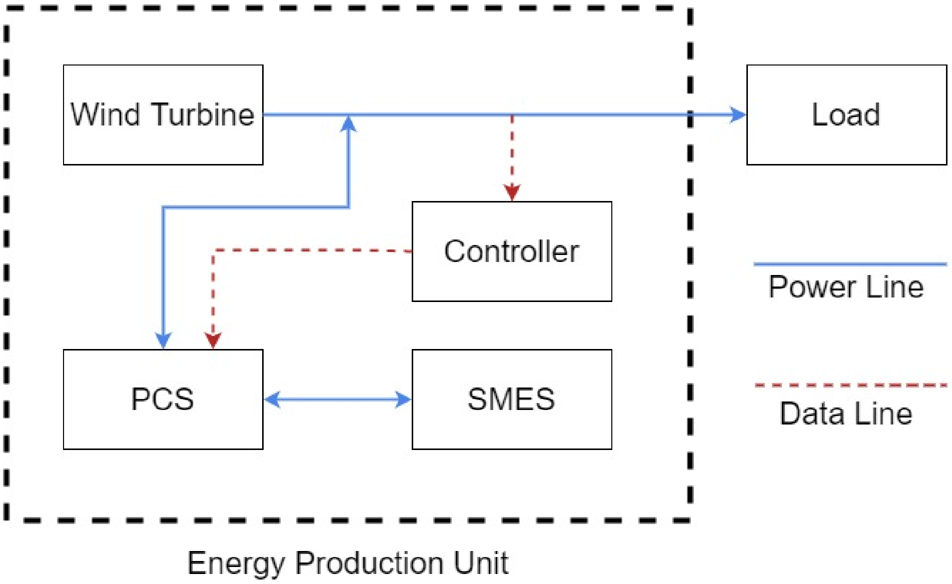

Figure 3.1: Diagram of the proposed architecture

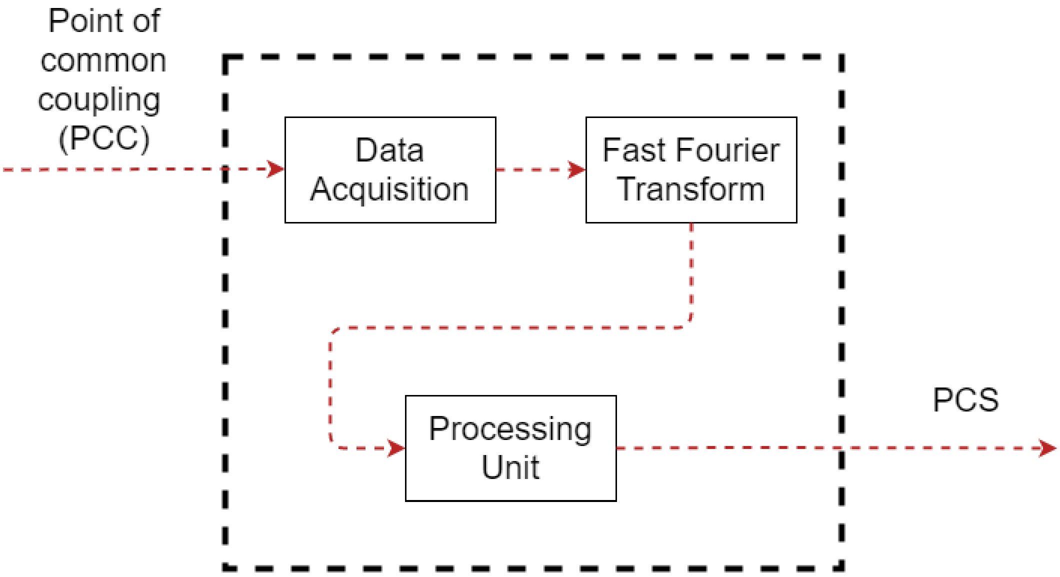

Figure 3.2: Diagram of the proposed controller

While building the simulation framework some problems arose; the problems encountered were related to Simulink constraints that caused the simulation to take a long time to complete, these long simulation times were not practical and changes were made to reduce simulation times; These changes caused both the data acquisition block and fast Fourier transform block to be removed. This new approach will be explained more thoroughly in the upcoming sections; it focuses on using the SMES for low-frequency harmonic correction, while the capacitor corrects high-frequency current harmonics. The work required separate simulations environments to observe pertinent behaviors, for this reason, various simulation scenarios were created, these are:

1. **correcting current harmonics caused by a non-linear load:** This scenario's primary objective is to create a baseline test where multiple simulations will be performed to better understand each component's response.
2. **correcting current harmonics caused by renewable generation:** A real-world example was developed to test a more practical simulation scenario, aiming to use the proposed architecture to correct and stabilize a renewable generation plant's energy production output, specifically a wind farm.

With further development of SMES technologies in mind, this thesis aims to help colleagues in future works by creating an open-source simulation environment where technologies can be integrated and tested, such as:

- more complex coil architectures.
- different SMES control strategies.
- responses of an active filter to different loads.

3.2 Framework

With convenience and future work in mind, a modular framework was chosen. It is a more sensible solution to understand and apply the desired architecture. This strategy becomes less work-intensive to remove and add components in the development stage of Simulink's simulation scenarios and control strategies. Before creating the simulation environment, some diagrams were created, Fig. 3.3 represents the high-level overview of the architecture, followed by Fig. 3.4 a more thorough diagram of the active filter. Fig. 3.5 is the final implementation in simulink with all the electrical components present. [16]

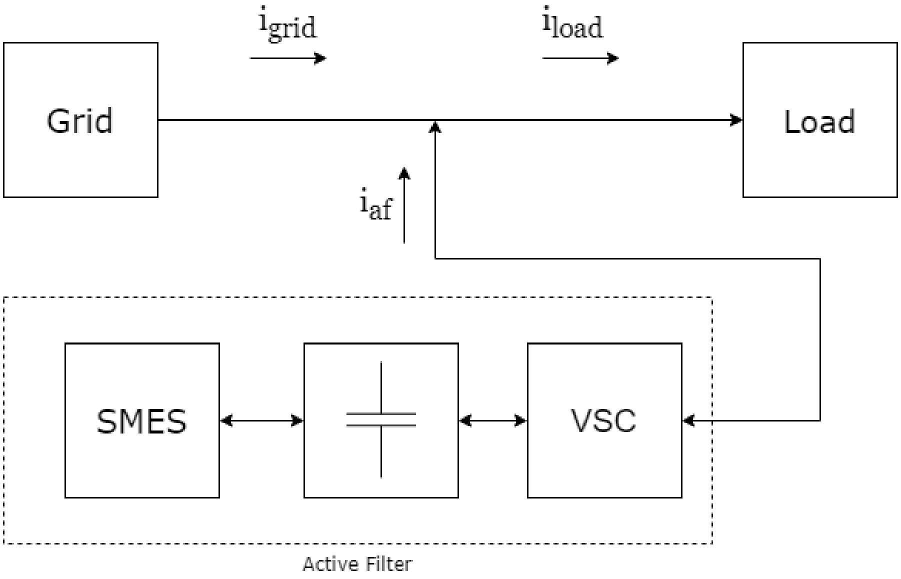

Figure 3.3: Diagram of the architecture

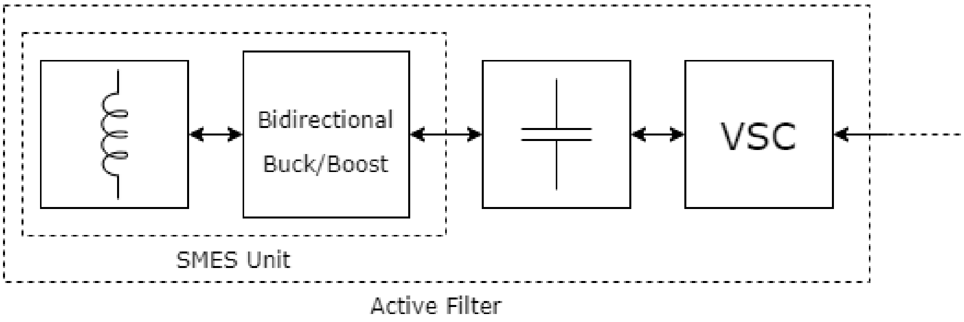

Figure 3.4: Diagram of the active filter

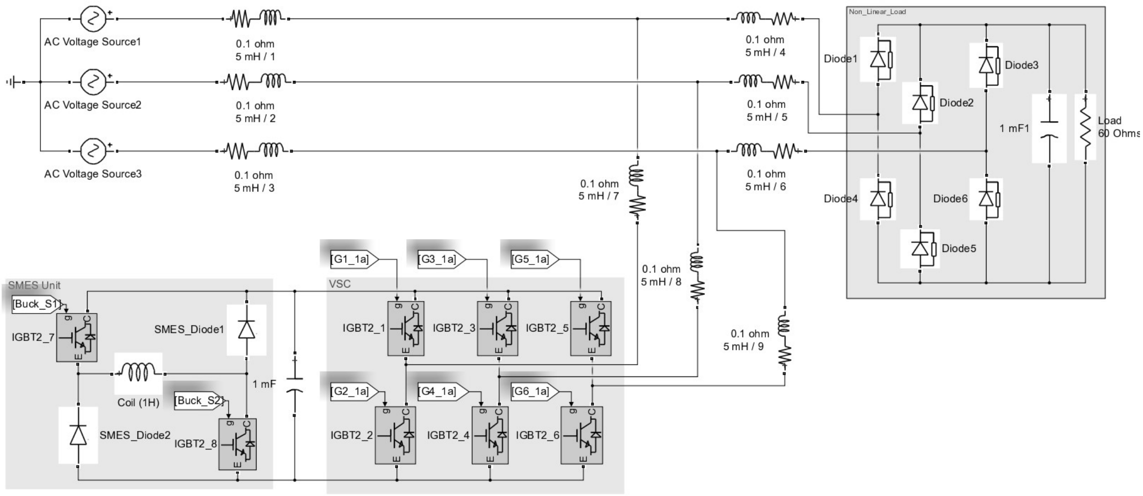

Figure 3.5: Simulink architecture implementation

3.3 Active filter implementation

3.3.1 Architecture

3.3.1.1 Overview

The used active filter comprises a VSC module that controls the energy transfer between the filter's energy storage components and the grid; these energy storage components are the capacitor and the SMES unit. The SMES unit needs to be controlled separately due to its intrinsic properties; a bidirectional buck/boost converter fills that role. Implementing the diagram shown in Fig. 3.4 resulted in the Simulink model shown in Fig. 3.6.

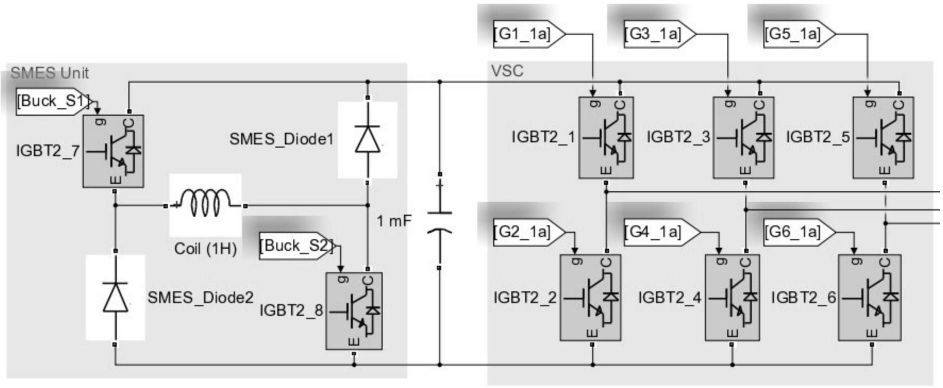

Figure 3.6: Simulink implementation of the active filter

Both the bidirectional buck/boost converter and VSC integrated in the active filter need control signals; these control signals are built and applied to the gate terminals of each component's IGBTs.

3.3.2 Control

3.3.2.1 Voltage source converter control

Park's transform was applied to the load current, causing it's three-phase signal to be transformed into two axes rotating with the same angular velocity as the fundamental sinusoidal phase quantities of the voltage grid. Applying a high pass filter to the previously obtained two-value signal, I obtain a signal that only contains the high-frequency component of the initial load current measured. Reverting the two-component signal to a three-phase signal using the inverse park transform, I obtain the reference current, Iref. A high level graphical overview of the described process is displayed in Fig.3.7. The diagram of Fig.3.7 was developed in Simulink and the result is displayed in Fig. 3.8.

Figure 3.7: System used to calculate Iref (high frequency harmonics)

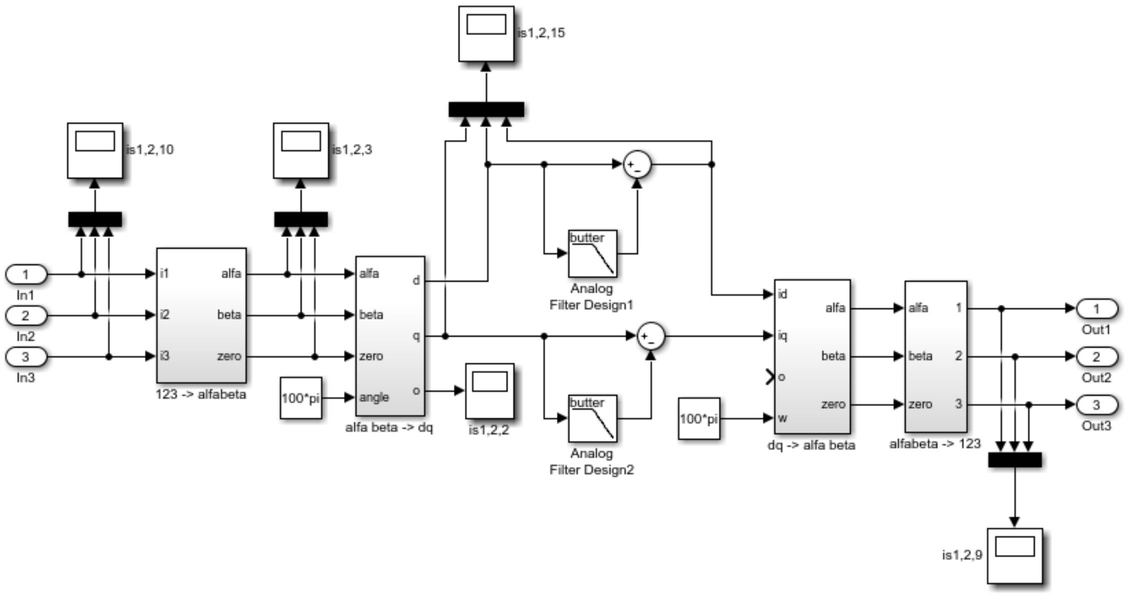

Figure 3.8: Non-fundamental harmonics calculation component diagram

Sampling the current injected by the active filter, I obtain the signal Iaf; the Iaf signal and the previously calculated signal, Iref, are processed, and Clarke's transform is applied to both signals. Subtracting the Iaf current from the reference current (Iref) and in turn passing it through a hysteretic comparator and a lookup table generates a input signal that correctly controls the VSC IGBT's. The previously described logic is graphically represented on Fig. 3.9, Fig. 3.10 and 3.11. The used lookup table used is displayed in Fig.

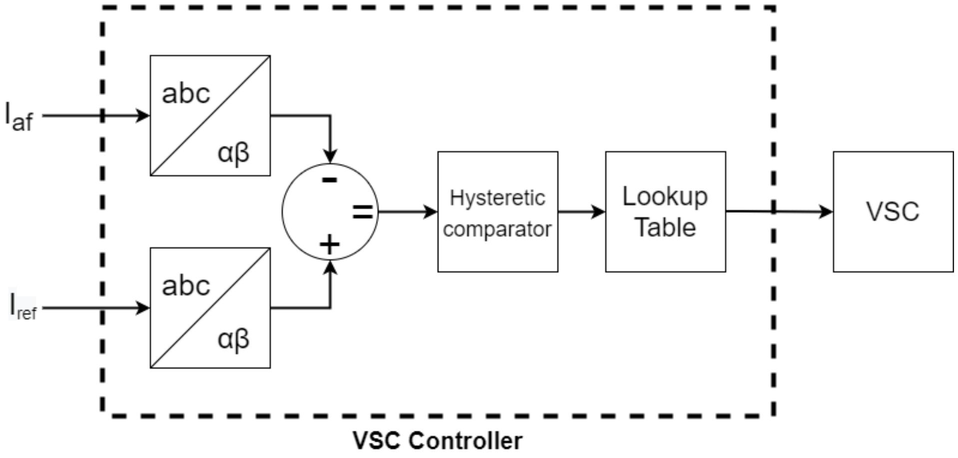

Figure 3.9: System used to generate the control signal supplied to the IGBTs of the VSC

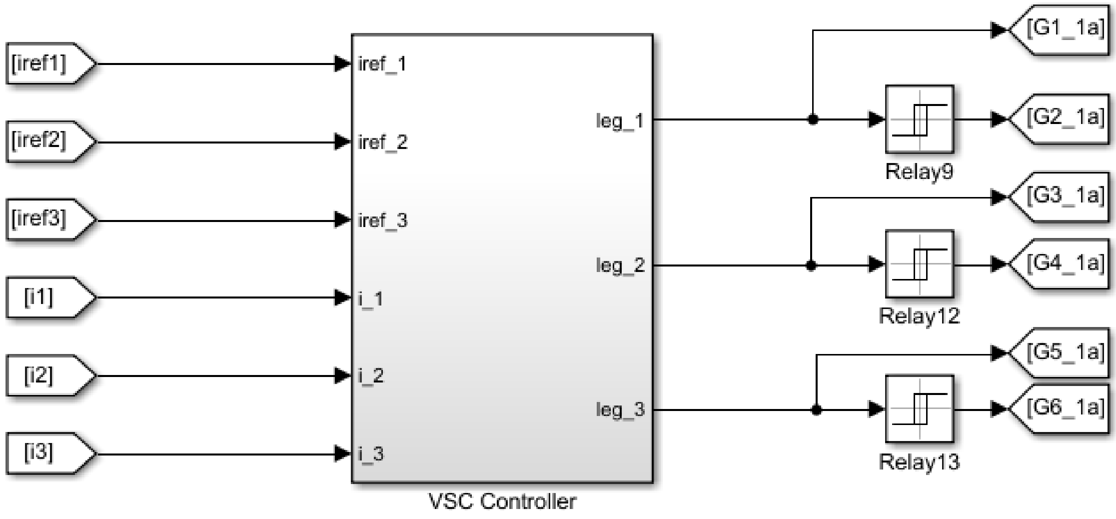

Figure 3.10: VSC controller block

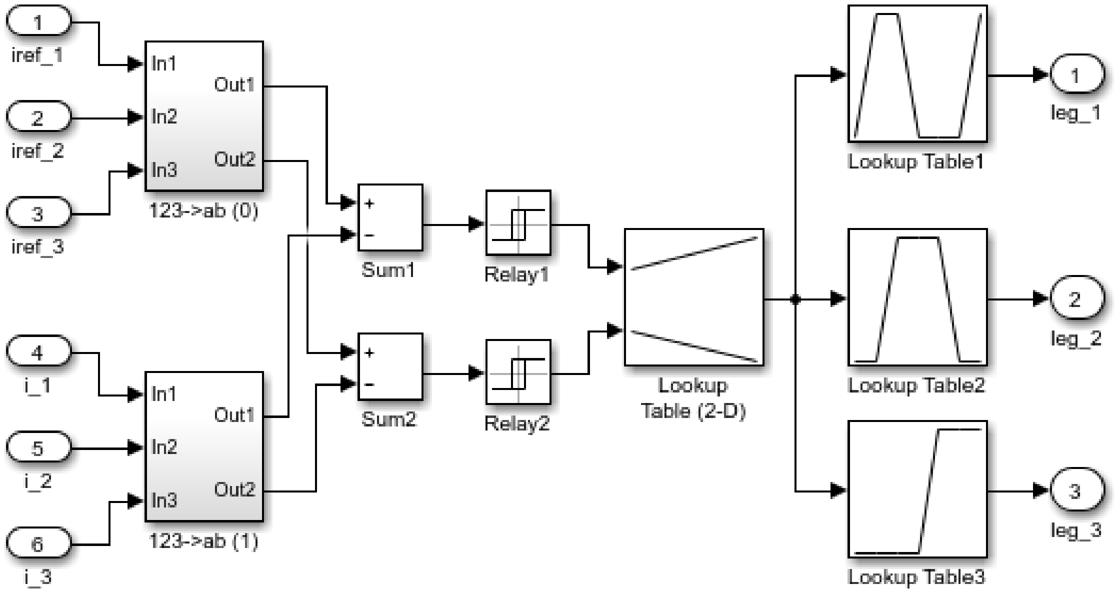

Figure 3.11: VSC controller component diagram

3.3.2.2 Bidirectional buck/boost converter control

The bidirectional buck/boost converter is crucial to SMES control since it needs to place the SMES unit in one of the following three states:

1. **Charging:** Both IGBT2_7 and IGBT2_8 are powered, leading to current flowing to the coil.
2. **Discharging:** Both IGBT2_7 and IGBT2_8 are unpowered, leading to current flowing out of the coil through the diodes and into the grid.
3. **Persistent:** On this state, IGBT2_7 and IGBT2_8 need to be in opposite states, this means that if one IGBT is turned on the other must be turned off, the current will then flow in a loop. This loop is composed by the coil, SMES_Diode1 and the IGBT that is turned on.

If the SMES is charged and not placed in one of these three states, the current flow will be blocked, and the coil will suffer an increase in voltage due to its high inductance leading to damage or even a total loss of the equipment. In the case of IGBT failure in the DC/DC converter, the topology assures the protection of the SMES coil, the current will flow through the diodes towards the capacitor in discharge mode. In this case, the VSC needs to handle this sudden surge of current to the capacitor and needs to detect it and discharge it to the grid, avoiding a capacitor overvoltage and protecting the VSC. The VSC protection referenced previously was not implemented in this work but it is an important point to take into account in a real-life application scenario. A malfunction of the cryogenic system is a dangerous situation and can cause the coil to lose its superconductivity, increasing its resistance and cascading into a damaged coil.

The VSC needs a DC voltage source as the energy supplier; this created a problem since the SMES unit behaves like a current source. To fix this issue and to couple the SMES unit to the capacitor and VSC, a control solution was implemented where the SMES unit charges/discharges in order to maintain a defined voltage at the ends of the capacitor, not allowing it to go below or above the defined threshold, this solution allowed the SMES to supply the bulk of energy while the capacitor sets the voltage.

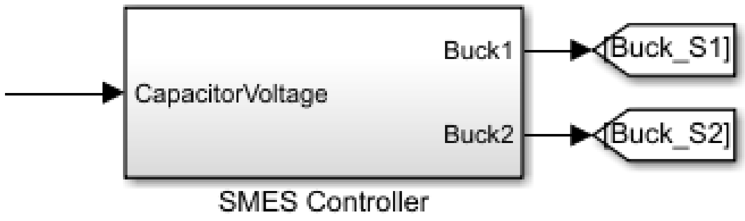

Figure 3.12: First version of the SMES controller containing only discharging

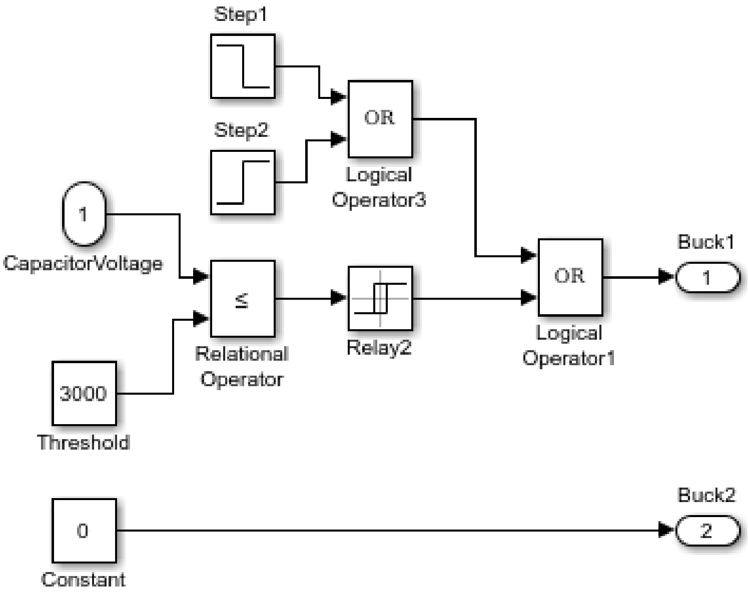

Figure 3.13: Simulink diagram of the first version of the SMES controller containing only discharging logic

During the control logic design phase, the main focus was the correction of harmonics, and for that reason, in early stages, the SMES current was set to 20 amperes, and multiple strategies were tested; the final architecture chosen is displayed in Fig.3.13. The solution's main building blocks are relational operators and logical operators; they seemed like the most logical and fast way to implement the idealized behavior.

After obtaining a solution for the discharging logic, a charging logic needed to be implemented so that the SMES unit could be charged during operation. The same building logic was used and added to the previous discharging logic obtaining the architecture displayed in Fig. 3.14 and Fig. 3.15.

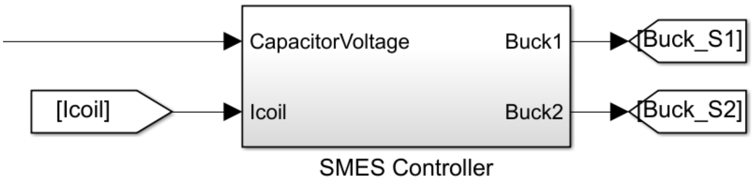

Figure 3.14: Second version of the SMES controller containing both charging and discharging

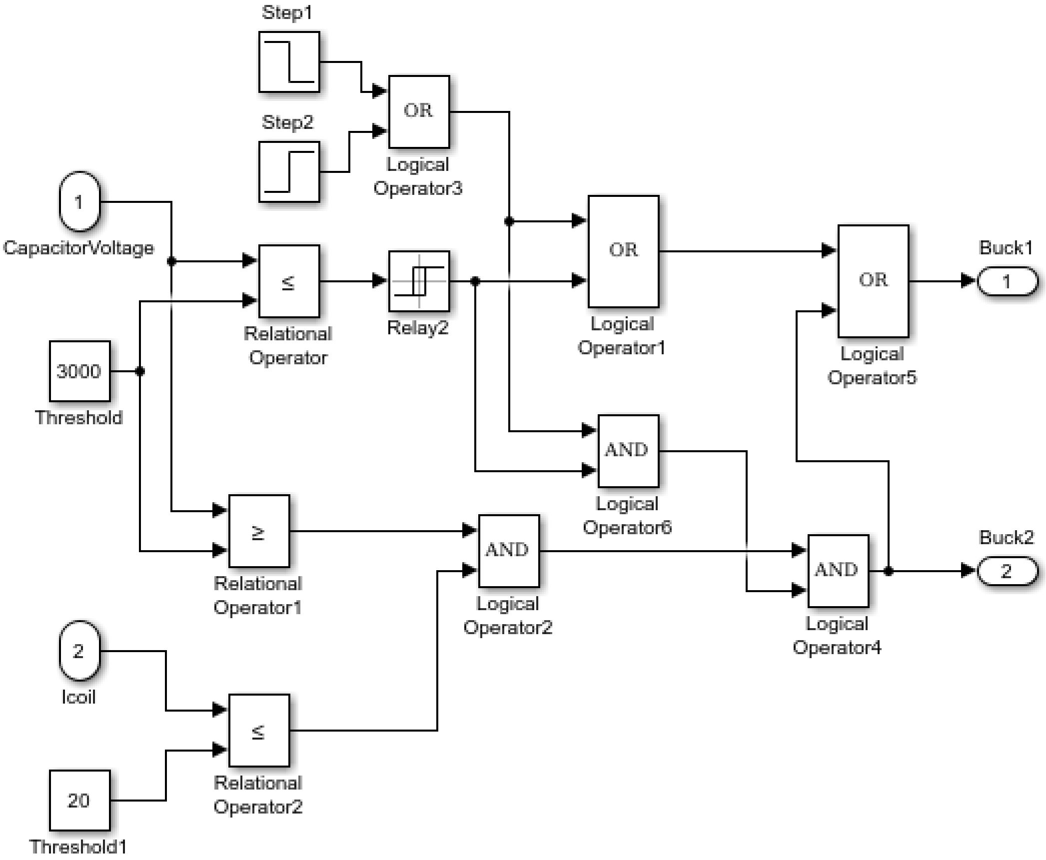

Figure 3.15: Simulink diagram of the second version of the SMES controller containing both charging and discharging logic

The capacitor threshold displayed on Fig. 3.15 controls the capacitor voltage with the use of relational operators, this assures the behavior explained previously. Both bidirectional buck/boost converter versions were tested in specific simulation environments, one of which the converter switches between persistent and charging mode and one which switches between persistent and discharging mode; additional logic is needed to join the two scenarios, this possible future work will be explored in the designed section.

CHAPTER 4

Simulation Results

4.1 Simulation scenarios

In this section of the practical work, the simulations made will be presented and analyzed;

All the simulations were made in a discrete environment with a sampling time of $5.14 * 10^{-6}$ seconds; this sampling time was found to be enough to observe all dynamic behavior.

The scenarios tested in the proposed framework and the corresponding simulation runs are presented in this section.

4.1.1 Current harmonics caused by a non-linear load

On the previous chapter, two main simulation scenarios were briefly explained. On the following, I will be diving deeper into the one entitled "correcting current harmonics caused by a non-linear load"this scenario can be split into different simulations.

The first simulation can be represented by a simple grid-load configuration, which created in order to observe the current supplied by the grid to a non-linear load; the grid used follows the standards of a Portuguese grid profile with a voltage of 230 volts at 50 hertz.

Fig.4.1 was the non-linear load used, composed by a diode bridge followed by a capacitor with 1 mF and resistance with 60 ohms in parallel. This load consumes currents with a lot of harmonics, the grid's three-phase current can be observed in Fig.4.2, this current is equal to the load current because the active-filter is not yet coupled.

To observe the behavior of the proposed active filter (Fig.3.6), it was coupled to the previous diagram. Too separate and better observe the result of adding the active filter without the SMES component, the SMES was decoupled, this simplifies the implementation

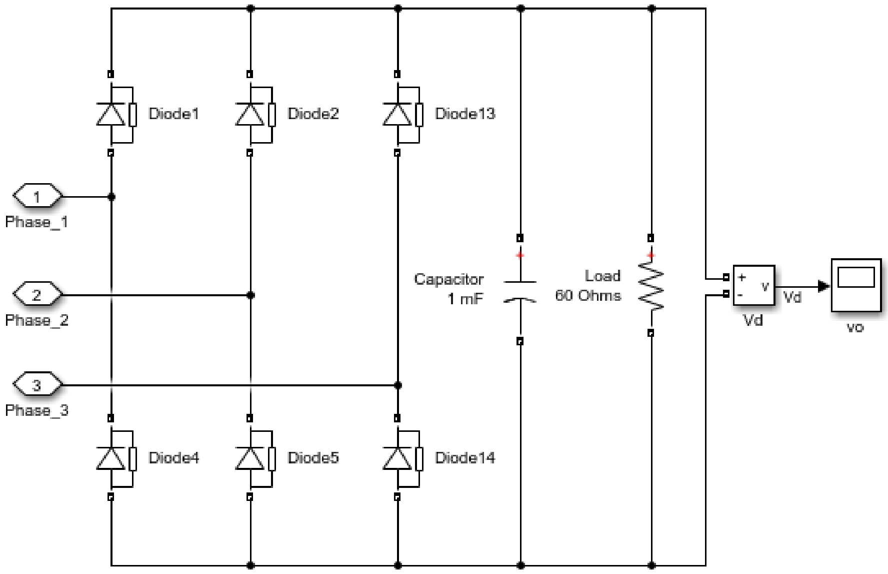

Figure 4.1: Non-linear load implementation on Simulink

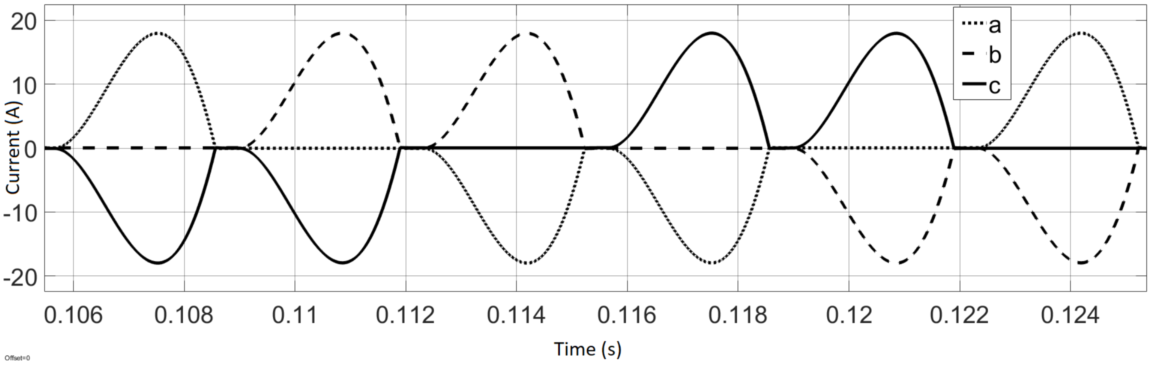

Figure 4.2: Grid's three phase current

diagram and the resulting implementation is represented in the block diagram of Fig.4.3 and the Simulink implementation of Fig.4.4.

The second scenario that was simulated on the referenced grid and load configuration, started by coupling the SMES unit to the simplified active filter, I obtain the model in Fig3.6; in this simulation, the SMES was previously charged and remained on persistent mode, until 0.92 to 0.98 seconds where the SMES control was turned on, and the results can be observed in Fig.4.8.

4.1.2 Current harmonics caused by renewable generation

Renewable energy production fluctuates depending on the amount of the natural resource available; for example, a solar array energy output fluctuates based on the amount of direct

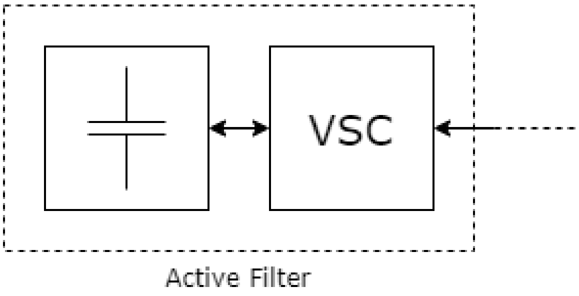

Figure 4.3: Active filter block diagram with SMES unit decoupled

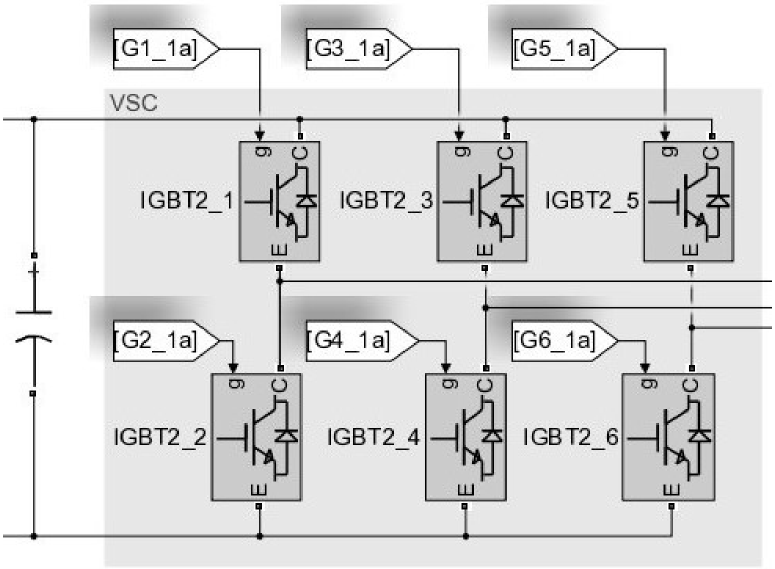

Figure 4.4: Active filter Simulink model with SMES unit decoupled

sunlight hitting the panel; the simulated use case is a wind farm where the amount of energy produced depends on the amount of wind available, this fluctuates over time.

To mimic a wind farm's behavior, a signal was synthesized by modifying a voltage source using amplitude modulation (AM) to simulate wind variation. Since wind variations are usually low frequency, a 5-hertz sinusoidal wave was chosen to be applied as the information signal in a traditional AM modulation.

Running the simulation software in the configuration composed by the load and generation with the previously referenced signal produced the resulting graph displayed in Fig.4.11.

Adding the proposed active filter in parallel with the grid-load model in order to observe the impact of the proposed hybrid capacitor/SMES active filter and running the simulation yielded the results on Fig.4.12.

4.2 Analysis of results

In this section, the active filter results obtained by running the simulation scenarios described in the previous chapter, including and excluding the SMES, are discussed.

4.2.1 Development tests

To more easily observe the implemented discharge logic's behavior, a test widow limited from 0.52 seconds to 0.92 was chosen; this can be observed in Fig. 4.5. The upper graphic of Fig. 4.5 shows the current through the coil while the bottom graph shows the current state of the SMES (controlled by the buck/boost); the switching observed on the bottom is caused by the discharging of the capacitor and subsequent charging; this is was allows the use of a current source in a VSC.

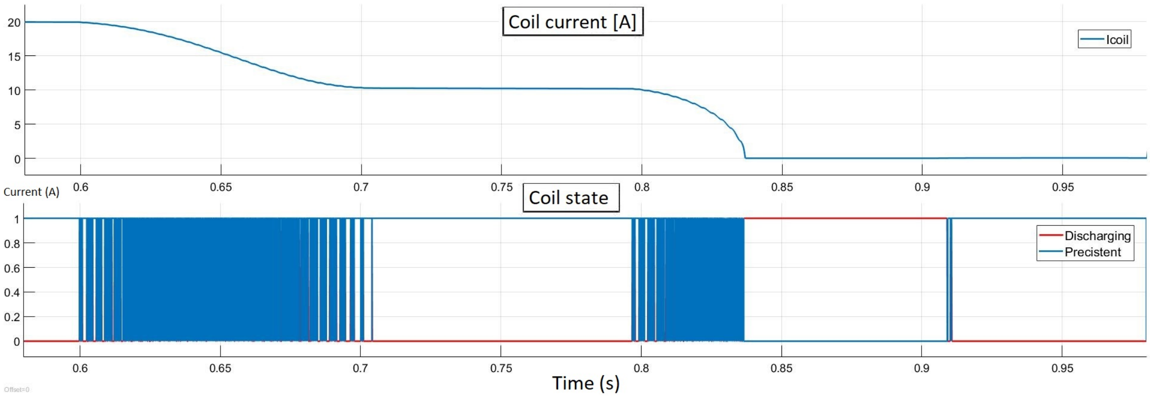

Figure 4.5: SMES discharge test

The implemented charge logic was also tested with a test widow limited from 1.45 seconds to 1.85 seconds shown in Fig.4.6. Similar to Fig.4.5 the bottom part of the graph shows the current SMES state; in this particular case the SMES cycles between charging and persistent.

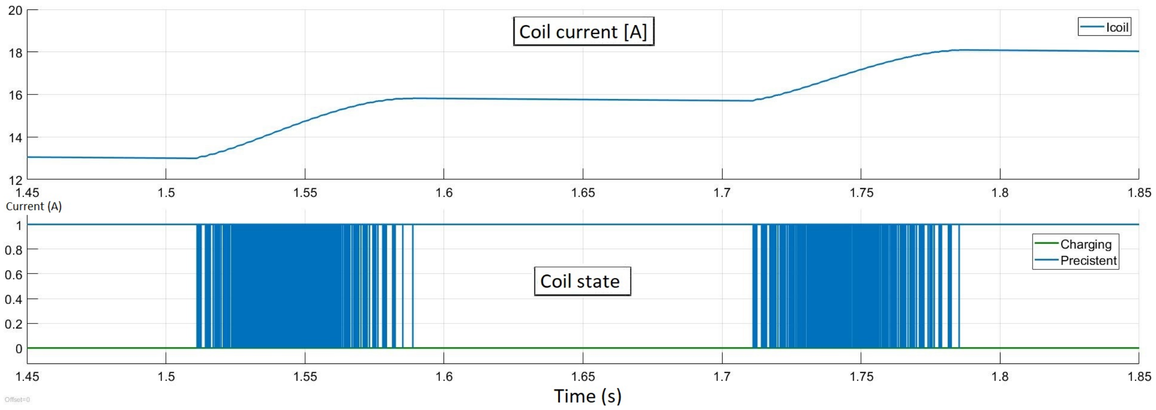

Figure 4.6: SMES charge test

4.2.2 Current harmonics caused by a non-linear load

Running a baseline simulation with a grid-load configuration yielded the current graph displayed in Fig.4.2, and it is evident that unwanted current harmonics are present. To remove these unwanted harmonics, the proposed active filter with the SMES uncoupled (Fig.4.4) was added in parallel with the grid-load model in order to observe the impact of the proposed capacitor active filter and running the simulation yielded the results in Fig.4.7, showing a major positive impact regarding the mitigation of harmonics.

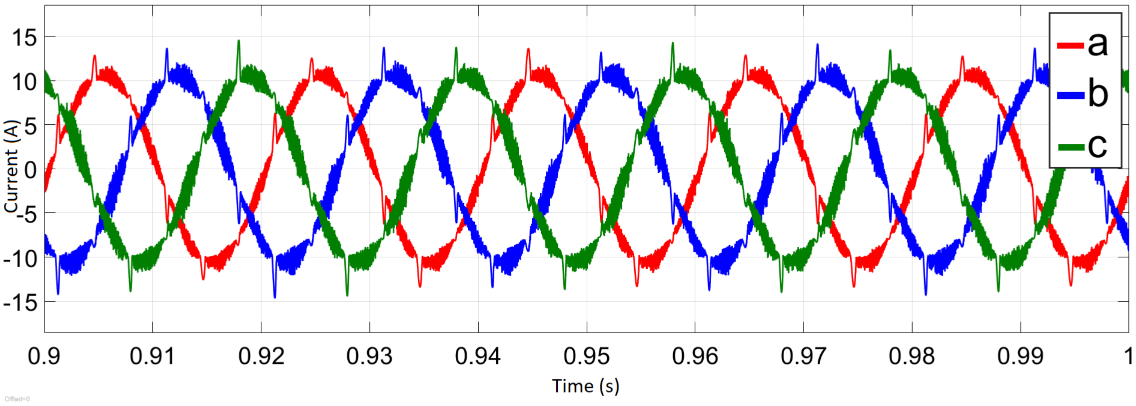

Figure 4.7: Grid's three phase current with SMES unit decoupled

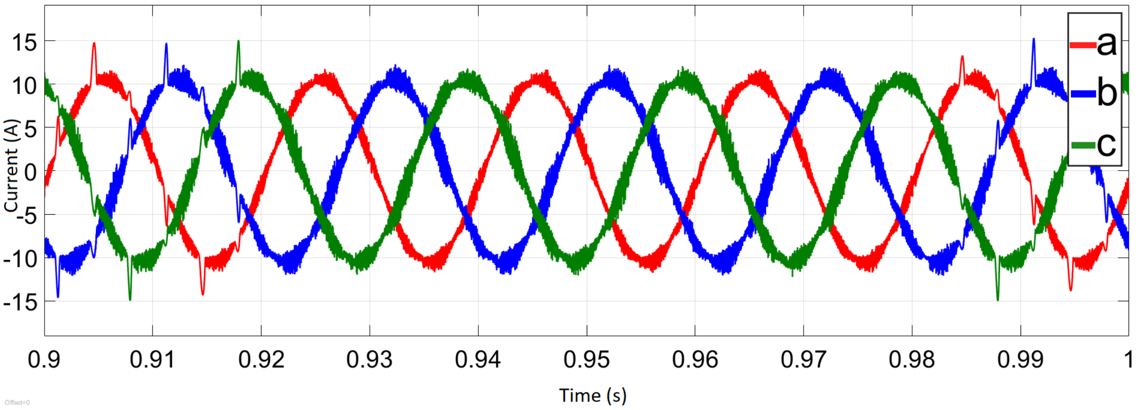

Figure 4.8: Grid's three phase current using active filter with SMES unit coupled

Although a good result was obtained, some unwanted spikes can still be observed. To solve this issue, a charged SMES was coupled to the active filter and discharged from 0.92 s to 0.98 s, obtaining the result in Fig.4.8; in this scenario, the harmonic correction is less noticeable and to more objectively quantify the correction the total harmonic distortion was calculated in both tests. Comparing the THD in both scenarios, i.e., the active filter without (Fig. 4.9) and with (Fig. 4.10), the SMES, it can be observed that phase A had the most significant improvement from nearly 12% to around 6% of THD.

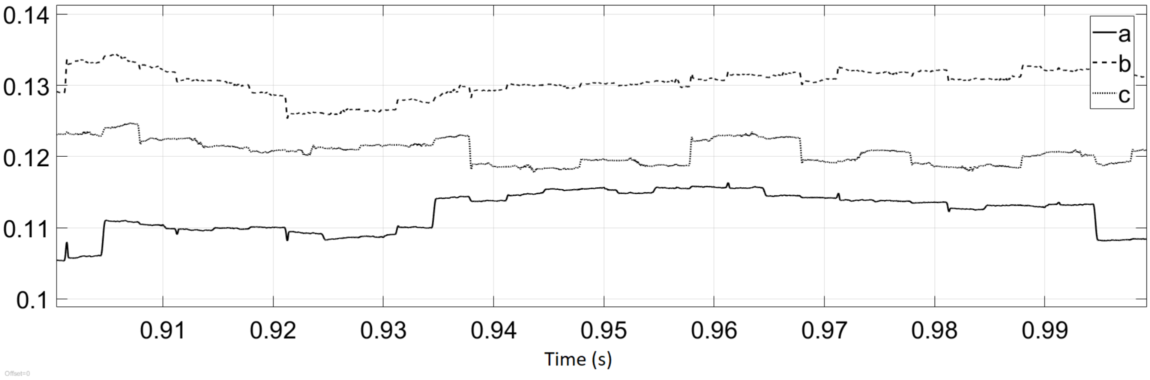

Figure 4.9: Total harmonic distortion of simulation present on Fig.4.7

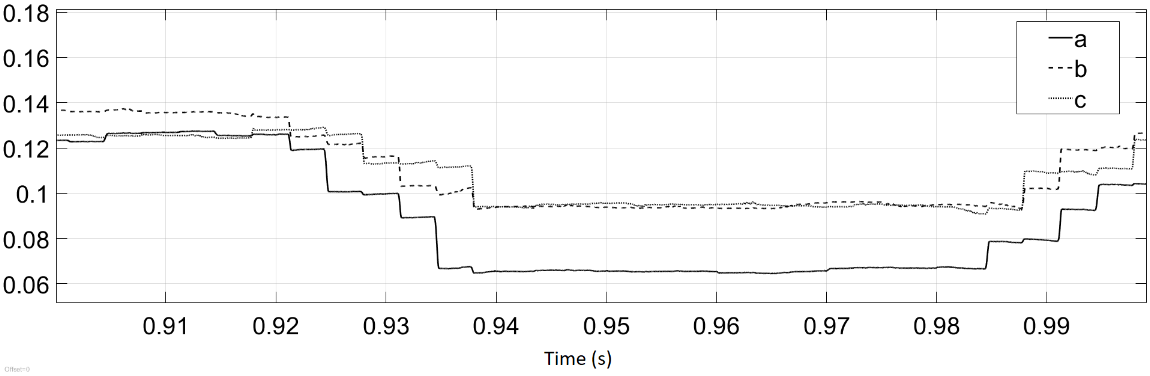

Figure 4.10: Total harmonic distortion of simulation present on Fig.4.8

4.2.3 Current harmonics caused by renewable generation

It was comparing the results of Fig. 4.12 and 4.11, that I managed to verify that the proposed architecture managed to reduce the grid's current harmonics, as well as the attenuation of the fluctuation induced by the simulated wind generator. This result confirms that this system also can compensate for the low frequencies imposed by wind intermittency. The IGBT switching caused some high-frequency noise, but this is expected and negligible compared to the current values displayed, and it can also be improved by filtering.

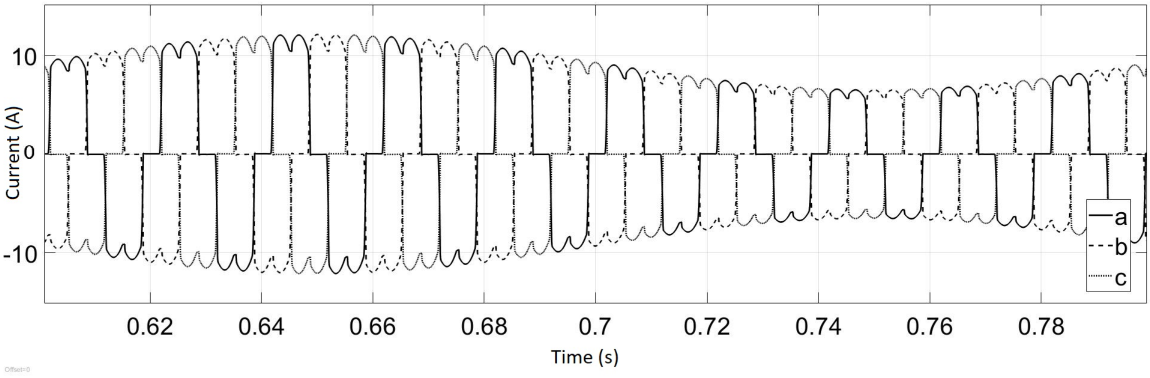

Figure 4.11: Three-phase grid current supplying the non-linear load

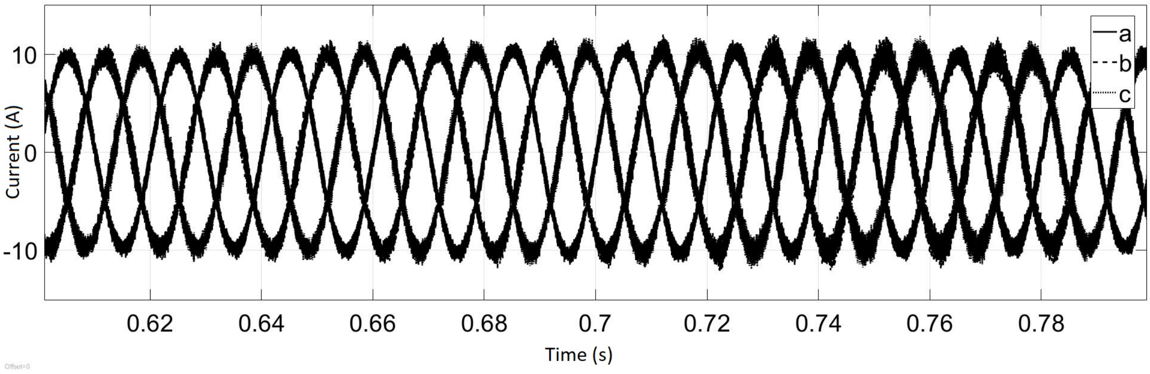

Figure 4.12: Three-phase grid current supplying the non-linear load with the active filter coupled in parallel

Chapter 5

Conclusion and future work

5.1 Conclusion

The objective of this work was to develop and simulate a system to remove current harmonics from the grid, using SMES technology; this was achieved by coupling in parallel active-filter to the grid and injecting current that would cancel out the undesired harmonics. A VSC based active filter was chosen due to being an easier and more practical solution, adding control logic to couple the SMES unit to the active filter. The results obtained were successful and impacted positively the grid, by removing undesired low and high-frequency harmonics. The analysis of the simulation results show good performance using the proposed active-filter implementation; results show that for high-frequency harmonics, the amount of energy stored by the capacitor is enough to support harmonic correction, adding the SMES did not impact significantly the correction of harmonics. This is not the case for low-frequency harmonics; in the case of wind farms, the amount of energy needed can justify the use of SMES if the power demand is high enough, in these specific cases the power supplied by a capacitor is not enough to support the correction, in this scenario the SMES is essential to perform an ideal harmonic correction. Creating a real-life simulation of this solution would have been interesting for a more practical analysis, but this was quickly dropped due to financial constraints and only software simulations were performed.

5.2 Future Work

5.2.1 Overview

One of the main focuses of this thesis is the creation of a framework where future work can be developed, this allows for a continuous stacking of information and reducing development times and catalyzing research; this section explores this proposal. Different control methodologies and implementation architectures can be simulated on top of the supplied simulation project; aiming to more easily and effortlessly test theorized behaviors streamlining a bit of the simulation testing.

The Simulink framework will be open-source to catalyze new work on this matter, using this framework more development can be made on a fully functional charge/discharge logic for SMES unit and do a more in-depth study of the behaviour using different architectures. A example of possible future works include: more complex and realistic SMES models, different PCS architecture and different generation behavior.

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