ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO ELECTROMECÁNICO (ESP. ELÉCTRICA)

The Problem of Flicker in a wave farm

Autor: Jaime Mayor de Juan
Director: Florent Morel y Eric Blanco

Madrid
Julio 2015

Jaime
Mayor
de Juan

THE PROBLEM OF FLICKER IN A WAVE FARM

Proyecto realizado por el alumno/a:

Jaime Mayor de Juan

Fdo.: …………………… Fecha: ……/ ……/ ……

Autorizada la entrega del proyecto cuya información no es de carácter confidencial

EL DIRECTOR DEL PROYECTO

Florent Morel y Eric Blanco

Fdo.: …………………… Fecha: 22/ 06/ 2015

Vº Bº del Coordinador de Proyectos

Fernando de Cuadra

Fdo.: …………………… Fecha: ……/ ……/ ……

UNIVERSIDAD PONTIFICIA ICAI ICADE COMILLAS MADRID

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

INGENIERO ELECTROMECÁNICO (ESP. ELÉCTRICA)

The Problem of Flicker in a wave farm

Autor: Jaime Mayor de Juan
Director: Florent Morel y Eric Blanco

Madrid
Julio 2015

Jaime
Mayor
de Juan

THE PROBLEM OF FLICKER IN A WAVE FARM

Table of Contents

Table of figures

Table of equations

Part I REPORT

EL PROBLEMA DEL FLICKER EN UNA GRANJA UNDIMOTRIZ

AUTOR: MAYOR DE JUAN, JAIME.

DIRECTORES: MOREL, FLORENT Y BLANCO, ERIC.

ENTIDAD COLABORADORA: ECOLE CENTRALE LYON.

RESUMEN DEL PROYECTO

Este proyecto trata de abordar el problema del flicker en una granja undimotriz. Está enmarcado en un proyecto de investigación francés “*Système houlomoteur Bilboquet*”, en el que la *Ecole Centrale Lyon* colabora junto con otras diez instituciones. Ha sido realizado en el área de Electrotecnia de la Ecole Centrale (“*Laboratoire Ampère*”), y este trabajo constituye una importante aportación para el adecuado desarrollo del proyecto, aunque pequeña, debido a las dimensiones del proyecto global.

Las energías renovables constituyen una alternativa a la energía que se obtiene de combustibles fósiles, que presentan el inconveniente de ser un recurso agotable y del impacto ambiental que comporta su utilización. En efecto, el progresivo aumento de la población mundial, la creciente demanda de energía, el constante incremento de los precios del petróleo y el calentamiento global, son algunos de los factores que han propiciado el desarrollo de las energías renovables. Cuentan a su favor con las siguientes ventajas: utilizan un recurso inagotable y gratuito; este recurso está muy distribuido por el planeta; los procesos tecnológicos asociados a la utilización de estas fuentes energéticas no son muy complejos y tienen un escaso impacto ambiental.

Algunas de ellas han experimentado una evolución espectacular, como la energía eólica. Respecto de otras, sin embargo, todavía no se ha explorado todo su potencial y la investigación científica y tecnológica sobre la misma se encuentra en un estadio inicial. Es el caso de las energías marinas. En la actualidad el

aprovechamiento de las energías marinas es mínimo y se limita a una serie de plantas localizadas en unos pocos países.

La energía marina puede clasificarse en distintas categorías en función del recurso energético que se intente explotar (undimotriz, mareomotriz, energía de las corrientes, térmica oceánica y osmótica). La energía undimotriz o energía de las olas es la obtenida a través de la captación de la energía cinética y al potencial del oleaje para la producción de electricidad.

El estudio del potencial de la energía undimotriz se intensificó a finales de los años 70, ya que, debido a la crisis del petróleo de 1973, empiezan a surgir (en Inglaterra Noruega, Suecia y Dinamarca, especialmente) los primeros programas destinados a investigar la producción a gran escala de la energía marina.

En 1994, la Unión Europea decide incluir la energía de las olas en su programa de Investigación y Desarrollo de energías renovables y, desde ese año, se han desarrollado en Europa más de una treintena de proyectos.

Podemos decir que posiblemente la energía undimotriz sea en la actualidad la fuente renovable marina con más proyección de desarrollo a nivel mundial. Este tipo de energías presenta una serie de ventajas que sin duda suponen factores decisivos en el impulso y apoyo en la investigación para el desarrollo de dispositivos que sean capaces de extraer la energía de las olas (lo que en inglés conocemos como "Wave Energy Converters"). Sin duda, el principal atractivo lo encontramos en la alta capacidad de predicción del comportamiento de las olas frente a otras fuentes de energía más variables, como el viento, lo que garantiza una mayor fiabilidad y regularidad en la obtención de energía. A su vez, si lo comparamos con su principal competidor, la eólica offshore, nos encontramos con que los dispositivos de extracción de energía de las olas marinas presentan una mayor facilidad de implantación (instalación más rápida, más económica y más sencilla, sin ser necesario el manejo de pesos pesados para los cimientos), una mayor densidad de implantación y de menor altura de la parte emergida (menor contaminación visual) y, por otro lado, un mayor potencial de implantación frente a otras energías, como la energía de corrientes marinas.

Sin embargo, este tipo de energías presenta una serie de limitaciones y complicaciones que dificultan el desarrollo de una tecnología optimizada y rentable. La principal dificultad la encontramos en el manejo simultáneo de dos variables principales: la altura de la ola y el período de la ola. En concreto este proyecto se centra en dar una respuesta adecuada a este problema.

El flicker es un fenómeno que nace precisamente de la inyección de potencias altamente fluctuantes a la red, debido a grandes variaciones de tensión en el punto de conexión de la planta de producción y la red eléctrica. Estas fluctuaciones de potencia se traducen en un parpadeo de las fuentes luminosas que pueden llegar a ser muy molestas, y que varían de unas fuentes a otras (las lámparas de incandescencia, por ejemplo, se ven afectadas especialmente) y de la percepción de unas personas a otras. En torno a esta cuestión existen estrictas regulaciones legales y limitaciones para los productores y, en el caso de este proyecto, las altas potencias (del orden del *MW*) con las altas frecuencias (menos de 1 *Hz*) conllevan a que el problema del flicker esté destinado a juegar un papel decisivo en la potencial implantación de la planta.

Este trabajo nace, por tanto, con el espíritu de tratar de solucionar el problema del flicker. Tras haber estudiado detalladamente el proyecto global y las características del dispositivo de extracción de energía, la primera fase del proyecto consistió en una búsqueda bibliográfica sobre las soluciones existentes en la industria. Entre las distintas soluciones, se decidió centrarse en una opción que consiste en un diseño de la distribución topológica optimizada de los dispositivos de extracción, de tal forma que cada dispositivo, al recibir la ola en un tiempo distinto, enviase las potencias a la red desfasadas las unas de las otras y al superponerse se limitasen las fluctuaciones respetando regulación legal.

Sin embargo, para poder tratar de comenzar a simular el comportamiento de la granja undimotriz frente al problema del flicker, era necesario tener un modelo unitario completo del dispositivo. A pesar de que había habido ya un trabajo previo sobre la modelización del dispositivo, lo cierto es que no existía ningún modelo general y explotable, lo que llevó a tener que ampliar los objetivos iniciales de este proyecto en el transcurso del mismo.

Por tanto, finalmente este proyecto acabó por tener dos vertientes: por un lado, un primer trabajo de búsqueda bibliográfica acerca del problema del flicker y soluciones en la industria, perfilando una de ellas para la continuación del proyecto global; y, por otro, el desarrollo de un modelo unitario del dispositivo de extracción de energía con la ayuda de los programas MATLAB® y Simulink®.

En definitiva y a modo de conclusión, este trabajo, que en un principio aspiraba a avanzar un problema que se preveía a largo plazo, finalmente presenta el tipo de solución y las herramientas bibliográficas en las que apoyarse para afrontar dicho problema y presenta a su vez un primer modelo del dispositivo de extracción de energía de las olas. Tal y como se ha dicho al principio de este resumen, no se trata de un gran avance en el proyecto global, dadas las dimensiones del proyecto (tras 3 años en los que lleva implicado el "*Laboratoire Ampère*" se sigue en la primera fase de concepción del proyecto), pero sin duda está enmarcado en una fase crucial en el correcto desarrollo del proyecto global (sobre todo el modelo unitario) y se dejan marcadas las líneas de actuación para la continuación del trabajo.

THE PROBLEM OF FLICKER IN A WAVE FARM

AUTHOR: MAYOR DE JUAN, JAIME.

DIRECTORS: MOREL, FLORENT Y BLANCO, ERIC.

COLLABORATING PARTNER: ECOLE CENTRALE LYON.

ABSTRACT

This project tries to deal with the problem of Flicker in a wave farm. It makes part of a French research project "*Système houlomoteur Bilboquet*", where the *Ecole Centrale Lyon* collaborates along with ten other institutions. It has been developed in the area of electrical engineering at the Ecole Centrale ("*Laboratoire Ampère"*), and this paper represents an important contribution to the proper development of the project, although small, due to the size of the overall project.

Renewable energy represents an alternative to energy obtained from fossil fuels, which have the disadvantage of being an exhaustible resource and because of the environmental impact involved in their use. Indeed, the progressive increase in world population, the increasing demand for energy, the steady increase in oil prices or global warming, are some of the factors that have led to the development of renewable energies. They count on the following advantages: they use an inexhaustible and free resource; this resource is widely spread across the planet; technological processes associated with the use of these energy sources are not very complex and have low environmental impact.

Some of them, such as wind power, have undergone a drastic evolution. Others, however, have not yet been explored to their full potential and scientific and technological research is at an early stage. It is actually the case of marine energy. Nowadays, the use of marine energy is minimal and limited to a number of plants located in a few countries.

Marine energy can be classified into different categories depending on the source of energy (wave power, tidal power, current power, ocean thermal energy

and osmotic power). Wave energy is obtained through the extraction of kinetic energy and potential of waves in order to produce electricity.

The study of the potential of wave energy was intensified through late 70s because of 1973's oil crisis, and it began to arise (specially in England, Norway, Sweden and Denmark) the first programs in research of production of large-scale marine energy.

In 1994, the EU decided to include wave energy in its program of research and development of renewable energy, and since then there have been developed in Europe over thirty projects.

We could say that probably wave energy is currently the most promising renewable resource in marine energy worldwide. This type of energy has a number of benefits which certainly represent key factors in driving and research support to the development of devices that are able to extract energy from the waves (what we know as "Wave Energy Converters"). Undoubtedly, the main attraction is found in the high predictability of the behavior of the waves against other resources highly variables such as wind energy, which ensures greater reliability and regularity in obtaining energy. Furthermore, when compared with its main competitor, the offshore wind, we find that the energy extraction devices of ocean waves have a greater ease of implementation (faster, cheaper and easier installation, without being required handling heavy weights to the foundation), a higher density of implantation and lower height of the emerged part (less visual pollution) and also a higher implantation potential compared to other energy sources such as marine current power.

On the other hand, this type of energy has a number of limitations and complications that hinder the development of an optimized and cost-effective technology. The main difficulty is found in the simultaneous handling of two main variables: wave height and wave period. Actually, this project focuses on providing an appropriate response to this problem.

The flicker phenomenon arises precisely after the injection of highly fluctuating power into the grid, due to large voltage variations on the point of common coupling of the production plant and the grid. These power fluctuations result in a flicker of light sources that can become very annoying and vary from one source to another (incandescence lamps, for example, are specially affected), and the perception of one person to another. Around this question there are strict legal regulations and restrictions for producers and, in the case of this project, the high powers (on the order of the *MW*) with high frequencies (less than 1 *Hz*) mean that the problem of flicker is destined to play a key challenge in the potential implementation of the wave farm.

This paper was born, therefore, in the spirit of trying to solve the problem of flicker. Having studied in detail the overall project and the characteristics of the wave energy converter, the first phase of the project consisted on a bibliographic research of existing solutions in the industry. Among the different solutions, it was decided to focus on the option of the design of an optimal topological distribution of the wave energy converters, so that each device received the wave on a different time, and then send the power to the grid in a time-shift, so when the powers were added, the fluctuations would be within the legal regulations.

However, in order to try to begin to simulate the behavior of the wave farm regarding the problem of flicker, it was necessary to have a complete model of the unitary device. Although there had already been previous work on the unitary model, the fact is that there was no general and exploitable model, which led to having to extend the initial objectives of this project in the course of it.

Therefore, this project finally ended having a double-nature: on the one hand, a first work of bibliographic research about the problem of flicker and solutions in the industry, outlining one for the continuation of the overall project; and the other, the development of a unitary model of the wave energy converter with the help of the MATLAB® and Simulink® programs.

In short and in conclusion, this work, which initially was intended to advance a long-term problem, finally presents the type of solution and bibliographic tools to address this problem and also presents a first model of the unitary wave energy converter. As previously said in this summary, it does not present a breakthrough in the overall project, given the size of the project (after 3 years that has been involved the "*Laboratoire Ampère*" in the project, they are still in the first phase of the project conception), but it certainly is contextualized in a crucial phase in the development of the overall project (especially the unitary model) and the main guidelines for further continuation of the work have been established.

Chapter 1 INTRODUCTION

Acknowledgement: this project makes part of a French project, *"Système houlomoteur Bilboquet"*, with different research institutions among which is "*Laboratoire Ampère*" of "*Ecole Centrale Lyon*", with whom I have worked.

In this chapter, an introduction of the project is made as a first approach to get familiarized with the concepts that will be presented later.

1.1 CONTEXT OF THE PROJECT

In order to adequately understand the following pages, it is important to place this work under its context. Firstly, we have to underline that this is not isolated project, as it intends just to make a small contribution to a big French project, *Système houlomoteur Bilboquet*, with different laboratories involved (for full list, please refer to *Part IIChapter 1*). Among these laboratories, we can find *Laboratoire Ampère* who is charged in the development of the electromechanical conversion chain. They have been working in this project for the past 3 years and they have foreseen a challenge in the long term related to the fluctuating voltage due to the oscillating condition of the wave power (the nature of this problem will be fully developed in the following pages). It is in this aspect where this paper was initially intended to make appearance. However, due to some complications and unexpected time limitations along the development of this work, the initial objectives had to be modified.

To be able to understand the organization of this work, and how the objectives had to be shifted, a brief introduction of the project should be presented. First of all, we may start by presenting the nature of the whole *Système houlomoteur Bilboquet* project, which lies on the extraction of wave power of the sea to be converted into electrical power. To do so, the partnering laboratories are trying to develop an oscillating system, commonly known as bobbing buoy (from now on we might refer it as its French name, "*bilboquet*"). The institution where this paper was originated, the *Laboratoire Ampère*, responsible of developing the electromechanical conversion chain, have realized that they will be having some trouble with the voltage fluctuations that produce what we call "flicker" of the light. The initial idea was for me to work on this subject, trying to find an economical solution to avoid these power fluctuations. That is why I started working in this area, searching for the solutions present in the industry and doing some research about the phenomenon of the "flicker" and the present regulations.

Once I had done all the bibliographic research, the next step was supposed to be a wave farm model implemented with *MATLAB*®, *Simulink*® and *Simpower*®. However, it was at that moment when we realized that we had to change the initial objectives.

When I arrived to the project, it had just been presented a thesis of the *Ecole Nationale d'Ingénieurs de Brest* (*ENIB*) that developed a first mechanical model, and a post-doctoral thesis of *Laboratorie Ampère* that made a thorough study of each of the components of the electromechanical conversion chain. Therefore, theoretically we counted on a developed unitary model of the *bilboquet,* just by the simple assembling of the two works. That way, we could part from that unitary model to create a model of a whole farm of bobbing buoys. Actually, the initial idea of this paper was to fight the problem of the flicker by studying the optimal topological distribution of the *bilboquets,* so we could reduce the fluctuations by a simple superposition of the power of each bobbing buoy displaced in space, i.e. in time (this principle is known as spatial averaging).

However, as the model of a single unit was not yet developed, we had to focus our efforts in this task. We could evidently use the results from the two previous papers. Nevertheless, as we advanced in the model we realized that they had difficult assembling due to the difference in time scales, and thoroughness of the models. The study made by the post-doctoral thesis of the *Laboratorie Ampère* was very precise and detailed, but far from being valid for an exploitable model (actually because of the level of detail of the research, that would need an excessive time to simulate a very short period of time).

For this reason, as the priority of the project as a whole was firstly to have an unitary model of the system, we decided to focus on a general structure for an exploitable model, that then could be improved and optimized. It is important to remark again the dimensions of this project, so we can understand why in this kind of research papers the initial ambitions have sometimes to be subjected to the priorities of the general project.

In conclusion, this paper can finally be divided in two big parts: on the one hand, we will present a model of a single unit of bobbing buoy and on the other hand a summary of the bibliographic research about the flicker, how to measure it and the solutions that have been implemented and those who are under research.

1.2 MOTIVATION

We are currently facing a time where renewable energies become an essential part of the electricity production. In 2013, renewable energy represented 21.7%[1] of the worldwide electricity generation and statistics prove that this number will probably rise in the next few years.

Now that the climate change has been stated as a fact, there is a global conscience that enhances the need of investing in new clean energies. The alarm of global warming, the emission of greenhouse gases, the need of transition away from fossil fuels and the wide range of possibilities that they offer, make these the energies of the future.

Among the different renewable energies, wave power represents a very attractive option for the future because of its potential and advantages over other renewable energies. There is an estimation that places the world's resource of this energy over 2TW[2], but the technologies for exploiting wave power are not very developed yet so they have not proven high performance. Some experts say that wave power is now where wind power was three decades ago[3], as researchers have not yet succeeded in finding an optimal design for the limitations of working in the sea (offshore technologies are always more expensive and more difficult to work with) and how to work with the variables of height of the wave and its period at the same time.

However, the good perspectives for the future are encouraging research in this area and investments in wave energy installations, with the hope of developing a system of control of this energy as performing and optimized as in the case of wind energy. The nature of this project lies on this hope and intends to add new advances to the technology for wave energy production.

The grid plays an essential role in the development of these new energies, as it represents the principal vector of transport to the consumer. In order to efficiently work with renewable sources, new technologies have been developed along with improvements in electronic power control, so new strengthened and polyvalent grids (often known as “smart-grids”) intend to have a better control of measurement (real-time metering, digital meters replace analog meters) and the possibility of managing high variable sources (wind, waves, sun). However, these kinds of new technologies always carry with them new challenges, and this paper will actually try to find a solution for one of these new challenges with the electric power.

1.3 OBJECTIVES AND PLANNING

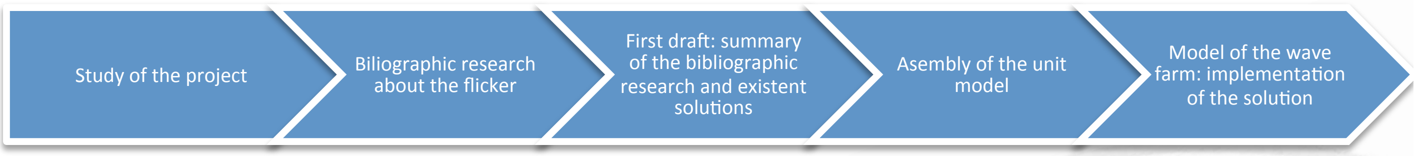
As it has already been presented in the previous subsections, it has to be distinguished between the initial and the final objectives and planning

1.3.1 INITIAL

The initial objectives of this paper were the following:

- Present the different regulations about the flicker limitations and measurement methods.
- Present the different solutions in the industry to the problem of flicker, and estimate which ones are viable for our project.
- Implement a solution based on the topological distribution of the bobbing buoys, in order to guarantee the limitations of the mentioned regulations of the flicker. This solution will be based on a model developed with *MATLAB*®, *Simulink*® and *Simpower*®.

In order to achieve these goals, the initial planning was the following:



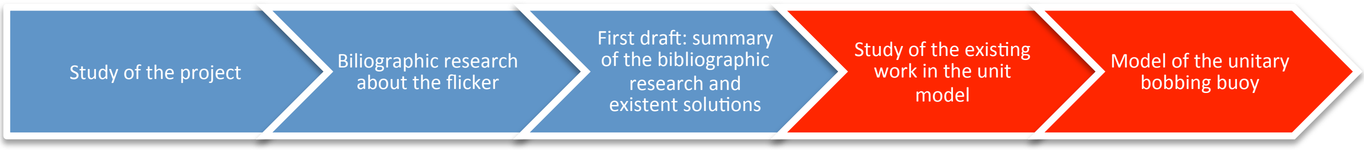
1.3.2 FINAL

However, the initial objectives had to be shifted to the following:

- Present the different regulations about the flicker limitations and measurement methods.
- Present the different solutions in the industry to the problem of flicker, and estimate which ones are viable for our project.
- Define a model of a unitary *bilboquet* developed with *MATLAB*®, *Simulink*® and *Simpower*®.

- Define a “perspectives” section so this work could be completed and improved in the future. In that section it would be established the path to follow the work already started.

The final planning resulted to be this one:



Chapter 2 THE PROBLEM OF FLICKER

2.1 *PRESENTATION OF THE PROBLEM*

One of the main objectives of this research project is to deal with the problem of power fluctuation, which is traduced in perturbations of the light that arrives to our houses. This phenomenon of variable light is commonly known as “light flicker”, and in this project power fluctuation is the result of the combination of the small frequencies of the wave (less than 1 *Hz*) and the big value of the power (some *MW*). We might be familiarized with the flicker, when the lights tend to dim or brighten or, for instance, when we notice that the light of the screen of our computer starts to flicker. Nevertheless, the appreciation of the flicker of the light may vary from one person to another, but there are some limits when it can become very disrupting for everyone and it is then where regulations take action.

In the wave power plant, each power take-off (PTO) consists on a dispositive called bobbing buoy (see Figure 1). This bobbing buoy was conceived following the model of the offshore petrol stations and it extracts mechanical power of the waves by a vertical movement of a floating plate along a concentric cylindrical buoy. The energy of this vertical movement is transmitted to a permanent magnet synchronous motor by a rack-and-pinion mechanism. This mechanical transmission dispositive, the power generator, the power electronics converters and the voltage transformer are all placed in the superior part of the spar. These kinds of wave energy converters (WECs) that use a not sea-based reaction source (in this case, the plate) are referenced as self-reacting WECs.

Here are some numbers in order to get an overview of the dimensions of the buoy and the orders of the magnitude of the whole wave farm (specific values can not be presented due to privacy reasons)[4]. About the dimensions of the bobbing buoy, the floating column's height is around 35 meters, and it is anchored to the bottom of the sea by a 3-mooring system. The floating circular plate, conceived for being very sensitive to waves motion, has a diameter around 25 meters and its movement will be guided along the column. The floating center is situated down the action of the wave, in order to limit the movement of the buoy. It is estimated that each buoy will be able to produce power of the order of 6 *MW*, and the idea is to place farms of 50 buoys in the Atlantic Coast, the Indian Ocean or the Pacific Ocean.

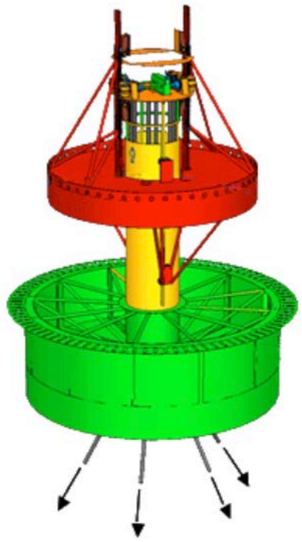


Figure 1: Bobbing Buoy[5]

With these orders of magnitude we are able to better understand the problem of the fluctuations in power. In the next section, it will be presented this phenomenon more in depth.

2.2 STATE OF THE ART

As it has been stated, electrical energy cannot be stocked (except for small power) so the production must be designed to satisfy the demand in real time. Therefore, a system of production, transport and distribution must be set in place in order to deliver energy to the consumer. In this chain, each element may be submitted to breakdowns and its nature might imply perturbations for the network. In addition, many other factors, such as severe climate conditions (in particular electric storms), the influence of the devices connected to the grid or other consumers' behavior, have a strong influence in the normal development of the chain production-transport-distribution-consumption.

All these anomalies might be taken into account when explaining why the network does not provide a perfect sinusoidal voltage with a frequency of 50 *Hz*. We might distinguish two main ways of measuring the voltage delivered to our homes: the continuity and the quality. The continuity makes reference to the number of voltage outages per unit of time and the quality of the electricity might be evaluated by the variations in value and frequency from the attended ones, and the absence of perturbations[6]. Among these perturbations, we can find voltage surges, voltage spikes, unbalanced 3-phase voltages or the flicker of the light. This project's intention is to study this last perturbation.

Voltage fluctuations are cyclical variations of the RMS voltage or a series of random voltage outages. It can be considered the flicker as disrupting when this fluctuations trespass the normal limits of ± 10% of the nominal value of the voltage. The most common definition of flicker places it as the "subjective impression of the light fluctuation" and the word "subjective" makes reference to the fact that its influence depends on the nature of the perturbation, the type of lighting and the observer. This fact makes even more difficult the study of this anomaly as a population study under different conditions is needed, and the measure equipment needs to be standardized.

The voltage fluctuations affect some light sources more than others (incandescence and discharge lamps specially affected) and they are mainly produced by brusque changes in the loads connected to the network (arc furnaces, arc welding, press, etc.)[7]. However, it may be produced too by generating power, especially by many new sources of energy, highly variables (wind, currents, waves, etc.). In the case that concerns this research, the rapid variations in the height of the wave produce a high power fluctuation, leading to voltage fluctuation at the point of common coupling (PCC). Considering the increase in the light flickering due to the development of these renewable energies, action is required to regulate this disturbing anomaly of the light, so there is a need to quantify it for then be able to set some limitations.

The role of the International Electrical Commission (IEC) is actually setting these standards and Europe is currently working under IEC's regulations. More precisely, most of IEC's standards in Electromagnetic Compatibility (EMC) are gathered in the IEC 61000 family, where they fix a method of measurement and the limits for voltage fluctuation. In this paper, a general overview of these measurement methods and limitations will be presented in order to be able to evaluate the performance of the wave farm studied.

Firstly, it will be presented the current standard measure technique defined in the IEC 61000-4-15 of 2003. Figure 2 shows a block diagram of the so-called standard "flickermeter":

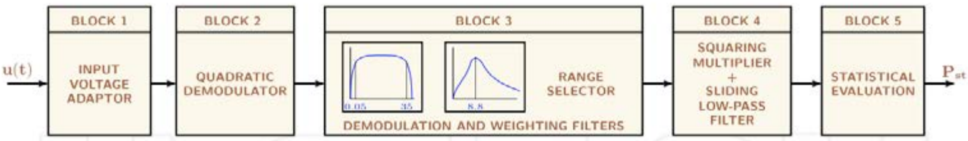


Figure 2: Block Diagram of the standard Flickermeter[8]

The flickermeter's objective is to provide an acceptable model of the behavior of the lamp-eye-brain system, given a voltage input. This diagram presents the different phases of manipulation of the input in order to determine whether the voltage fluctuations are translated in the disturbing phenomenon of the light flickering or not. The light source defined by IEC in this model is an incandescent lamp, nominal power of 60 W at 230 V for 50 Hz systems. Here is a brief description of each block[8], [9]:

- **Block 1: Input Voltage Adaptor**. In order to guarantee the independence of the voltage input, the input is scaled with respect to its average value. It is usually connected to the secondary winding of a voltage transformer, and it avoids the modification of the relative voltage fluctuation, ΔV/V (%). It presents a constant time of 1 minute.

- **Block 2: Quadratic Demodulator**. Considering that the voltage fluctuations are proportional to the fluctuations in luminosity of the incandescence lamp (ΔJ/J =γ ΔV/V), we can define as input to this block a modulated signal with a sinusoidal carrier of 50 *Hz*. A quadratic demodulation is applied to the signal in this block in order to obtain the voltage fluctuation.
- **Block 3**: **Demodulation and Weighting Filters**. This block is the first one that makes reference to human perception of the flicker, and it represents the eye perception. It is composed of three filters and one measurement scale selector. The first filter is a 1st order Butterworth high-pass filter with a cut-off frequency of 0.05 *Hz*, in order to remove the continuous part of the signal. The second, is a 6th order Butterworth low-pass filter with a cut-off frequency of 35 *Hz*, and its function is to attenuate by 55 *dB* the frequencies near two-times the network frequency (2x50 *Hz* = 100 *Hz*). To these two filters, that remove the frequencies not perceivable by the human eye, we add a weighted pass-band filter, based on a threshold curve of perceptibility obtained experimentally by H. de Lange (de Lange, 1952; 1961). This last filter adds an attenuation of 37 dB to the frequency of 100 *Hz*. Finally, although it can be placed either after or before the filters, there is a measurement scale selector that selects the output of the filters to adjust the sensitivity of the equipment to the value of relative voltage fluctuation.
- **Block 4**: **Squaring-multiplier + sliding low-pass filter**. In this phase, the perception of the human brain to the flickering is taken into account. Firstly, the signal is squared to simulate the non-linear behavior of the human eye and brain simultaneously. The brain’s memory is represented by a first-order sliding low-pass filter with a time constant of 300 *ms*.
- **Block 5**: **Statistical evaluation**. This last phase receives as input the instantaneous sensation of the flicker, and it must evaluate the severity of

the flicker, i.e. quantify the “level of annoyance”. It implements a statistical study after sampling the signal. Although the calculations will not be presented in this paper, it is important to distinguish two different observation periods: short-term flicker severity, P_{st}, usually fixed to 10 minutes, and long-term, P_{lt}, usually 2 hours[10]. Under the circumstances defined previously, with the incandescence lamp and respecting the calculations established by the IEC 61000-4-15, the annoyance threshold is set at P_{st}=1, that represents the perception for 50% of the population[11]. Below this limit, the light flickering might be perceived, although it is not considered as disturbing. However, the flicker emission at the Point of Common Coupling (PCC) is limited by the IEC for Distribution (MV) Connections to Pst=0.9 and Plt=0.7, and to Pst=0.8 and Plt=0.6 for Transmission (HV) Connections[12].

2.3 SOLUTIONS IN THE INDUSTRY

To avoid or at least reduce considerably this disrupting phenomenon, there are many possible solutions in the industry. Here are some solutions proposed in [13]:

- **Energy storage**: electrical (super capacitors, batteries…) or mechanical (flywheels, hydraulic accumulators…).
- **Control strategies**: after statistics studies we can avoid the cumulating of power fluctuations.
- **Reactive power compensation**: controlling the reactive power injected in the grid by devices such as static synchronous compensators or grid connecter inverters.
- **Increasing short circuit power**: adapting the electrical network at the point of common coupling in order to limit the power fluctuations.
- **Spatial averaging**: designing an optimized disposition of the PTOs in order to cancel the effects of power fluctuation by the superposition of the

power of each WEC shifted in time. This will be the desired solution for this project, as it is the most performing from the technical and especially economical point of view. However, it is important to remark that some of these techniques are not incompatible, and they might be combined. Actually, in the long term for this project, it would probably be the best option.

Regarding this last possible solution, there has already been considerable research that has proven some interesting results about this method. Especially remarkable for the purposes of this project is the research about the implementation of this method in the Fred Olsen (FO) Wave Energy Project, and the PTO known as the “Lifesaver”. Some research institutions, such as the *Norwegian University of Science and Technology*, the *Chalmers University of Technology* in Sweden or the *Norwegian University of Life Sciences*, have considered the option of power smoothing by an optimal topological configuration of the WECs.

Nevertheless, it is important to highlight that there are some considerations to be made about the differences between the FO project and our own. For example, in their project the power is only produced in one of the senses of motion of the PTO, whereas in our project it is produced in the two senses. In addition, the dimensions of the generator and the power produced are considerably different in both projects (around the *MW* in our project and between 30-600 *kW* by device in the FO project[14]).

Bearing in mind this appreciation, now we will present some research papers that may concern our project, and just mention some other relevant bibliography that might be consulted for the implementation of a solution to the problem of the flicker for this project in the future. We will notice that the references are very recent, because this idea is becoming more and more conceived in the emerging wave power technologies, hence its interest.

- Probably, one of the most valuable and helpful documents, if not the most important, to understand the FO project and the most performing techniques in wave power conversion is the Thesis for the degree of Philosophiae Doctor of Jonas Sjolte, ***Marine renewable energy conversion: Grid and off-grid modeling, design and operation***, July 2014[14]. Especially, concerning *Chapter 4*, *Wave farm design*, where it explains how the topological disposition should be conceived. However, it does not limit its research to the farm design, as it also presents a general overview of wave energies, a detailed description of the system "Lifesaver", and a model proposed.

- The research paper ***Power Smoothing by Aggregation of Wave Energy Converters for Minimizing Electrical Energy Storage Requirements***, 2007[15], which is actually limited to the study of this of spatial averaging. It could be another interesting starting point that needs to be improved, as it considers a very simple model to study this technique for avoiding power fluctuations based on a simple trigonometric principle, but it neglects the hydrodynamic forces produced between each PTO, which are in fact quite remarkable. In this paper, they state that the optimal averaging occurs when control strategies of reactive and latching control are used.
- Some other interesting points are made in the article ***Exploring the Potential for Increased Production from the Wave Energy Converter Lifesaver by Reactive Control***, July 2013[16], where they add significant information about the control strategies of the WEC. They study the performance of the reactive control technique in wave power extraction. However, it is important to remark that our project counts with an advantage over the "Lifesaver" device, as theoretically our PTO will generate power both in the up going a down going motion of the bobbing buoy, whereas in the case of the "Lifesaver" they generate power in the up going movement of the PTO but they get power of the grid to tighten the mooring line in the down going motion, thanks to the bidirectional sense of the converter (see Figure 3). This

characteristic of their PTO contributes to some problems in the wave power extraction that we would not be facing.

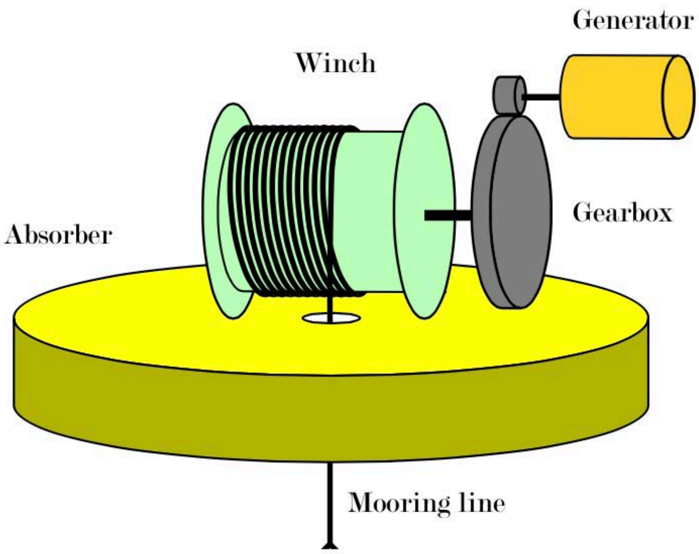


Figure 3: Schematics PTO "Lifesaver project"

Additionally, they present a model of the converter that apparently reduces the time of simulation and will not need a filter to avoid the limitations in Total Harmonic Distortion (THD[1]), but our model does take into account the filter, as we will present in *4.4*.

Another interesting aspect presented here, but that is also presented in other articles such as [17][18][19], or the previously mentioned study [14], is the connection of the PTOs in a wave farm. They affirm that in an optimal conception of the wave farm, the PTOs should be connected to the DC part of the back-to-back structure, in parallel with the capacitor (see Figure 4). This would be cheaper from the point of view of the number of power electronic components as well as the dimension of the capacitor, as the power fluctuation cancellation due to the spatial configuration will already be taken into account.

[1] The THD is a measure of the ratio of the RMS value of the sum of harmonics to the fundamental frequency value

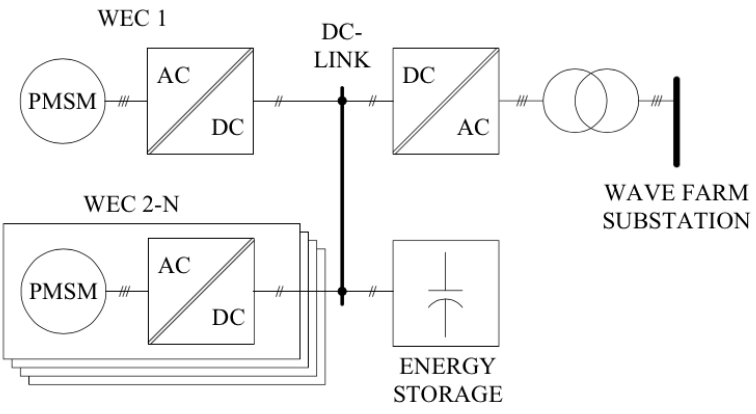


Figure 4: Wave farm connection of PTOs proposed[18]

However, we should note that currently our project is not designed to be able to admit this kind of connection, because each PTO is intended to be sold in units, so the connection would be at the end of the converter, on the side of the grid. Actually, Figure 5 would be a rudimentary model of how we would connect two PTOs with the current conception of the system. For a given height of the wave *Hcc* each bilboquet unit will perceive it differently, therefore the superposition of the different powers (*I1* and *I2*) will guarantee an adequate level of flicker, *Pst*.

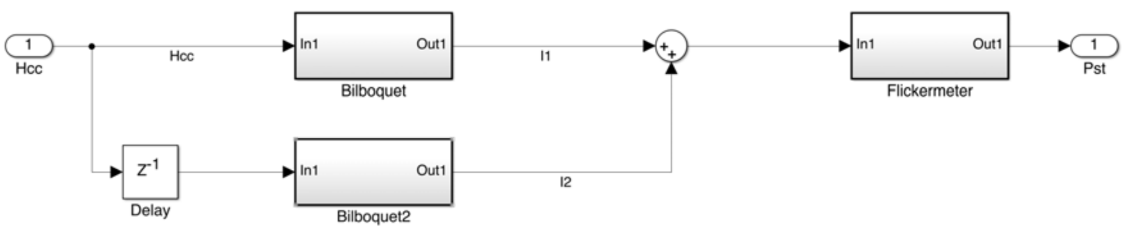


Figure 5: Wave farm connection in the project "Bilboquet"

Some other bibliography that might be of interest about the FO Project and the "Lifesaver" concerning our project would be [17], [18], [19], [20], [21] and [22]. However, it must be said that many concepts are redundant with the information presented in the previous three documents that have just been presented.

Chapter 3 SYSTEM DESCRIPTION AND ORIGIN OF THE PROBLEM

In this section it will be described more in detail the project "*Système houlomoteur Bilboquet*", specially the electromechanical conversion chain in order to understand the whole process from the variation in height of the wave to the problem of the flicker.

3.1 WAVE ENERGY

The first step to understand the system studied in this project is to understand the origin of the energy: the mechanical energy of the wave. However, the following description will be a general overview, as it is not essential a deep knowledge of wave modeling to be able to face the problem of the flicker or for the model that concerns us.

The sea waves have its origin on the wind, who depends itself on the degradation of the solar radiation. That is why the characteristics of the wave vary strongly depending on the geographical situation and the climatic conditions. Figure 6 shows how the geographical situation constitutes a key factor in deciding where to place the wave farm.

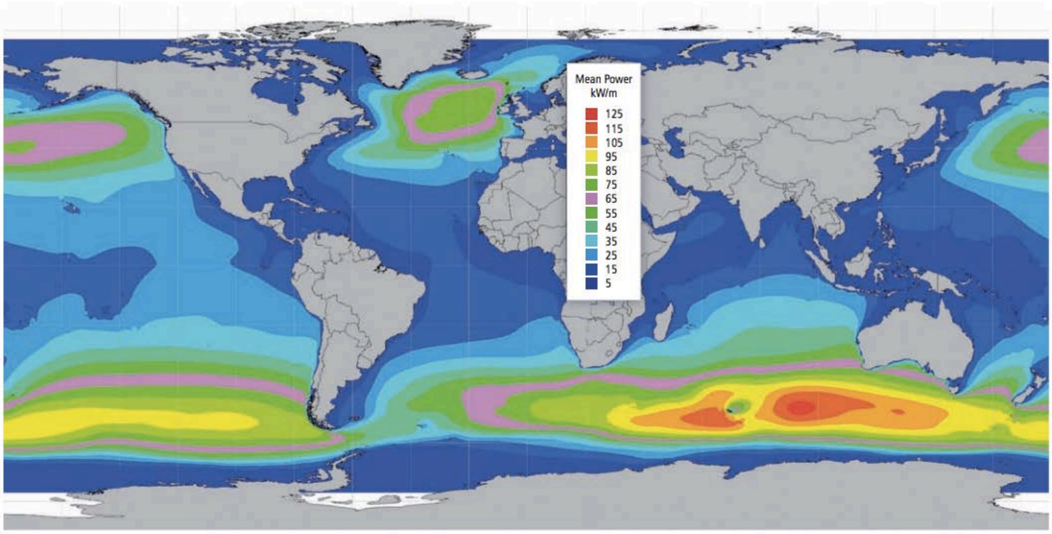


Figure 6: Global distribution of wave power[23]

By the mathematic description of a wave, it can be obtained the energy density of a water column with a height difference of H_{cc} (cf. Figure 7).

$$\frac{E}{S}\left(\frac{J}{m^2}\right) = \frac{1}{8} \times \rho \times g \times {H_{cc}}^2$$

Equation 1: Energy Density of a monochromatic wave

Where H_{cc} represents the variation in height of the wave, ρ the density of the water and g the acceleration of the gravity ($9{,}8\ \frac{m}{s^2}$).

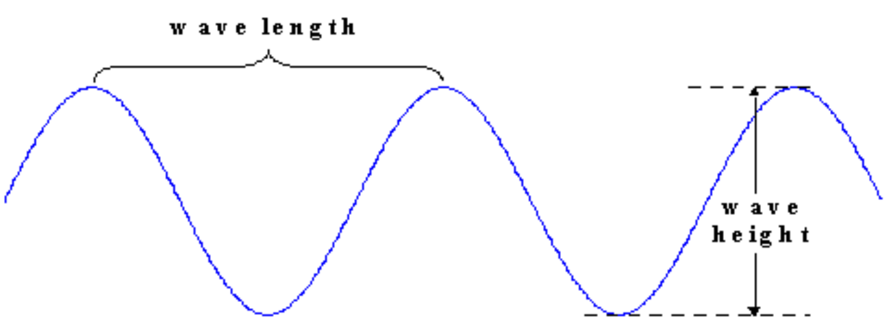


Figure 7: Monochromatic and unidirectional wave[24]

If we consider the whole wavefront, under some simplifications we may obtain an expression of its linear power density. It states that the power per meter depends on the square of the height of the wave H_{cc}, and the period T of the wave :

$$P_w\left(\frac{W}{m}\right) \approx \frac{\rho \times g^2}{32 \times \pi} \times H_{cc}^2 \times T$$

Equation 2: Power linear density of a wavefront

However, it should be noted that in reality this expression is far from precise, because in this calculation the wave has been considered as monochromatic and unidirectional, while sea waves are polychromatic and random. Although the expression is not precise, what is interesting for our study is that even considering the fact that the waves are polychromatic and random there is a square dependency on the height of the wave and a direct relation with the period of the wave.

3.2 ELECTROMECHANICAL CONVERSION CHAIN

In this section the already introduced principle of electromechanical conversion will be presented more in depth. The mechanical energy of the wave is transferred to the PTO through the variation of height of the wave by a rack-and-pinion mechanism. By this mechanism, the vertical movement of the buoy is converted in rotational movement of the permanent magnet synchronous motor, placed on top of the spar. This kind of wave energy converter (WEC) is called self-reacting point absorber, because its reaction source, i.e. the plate, is not sea-based, and the dimensions of the buoy are small compared to the length of the incident wave.

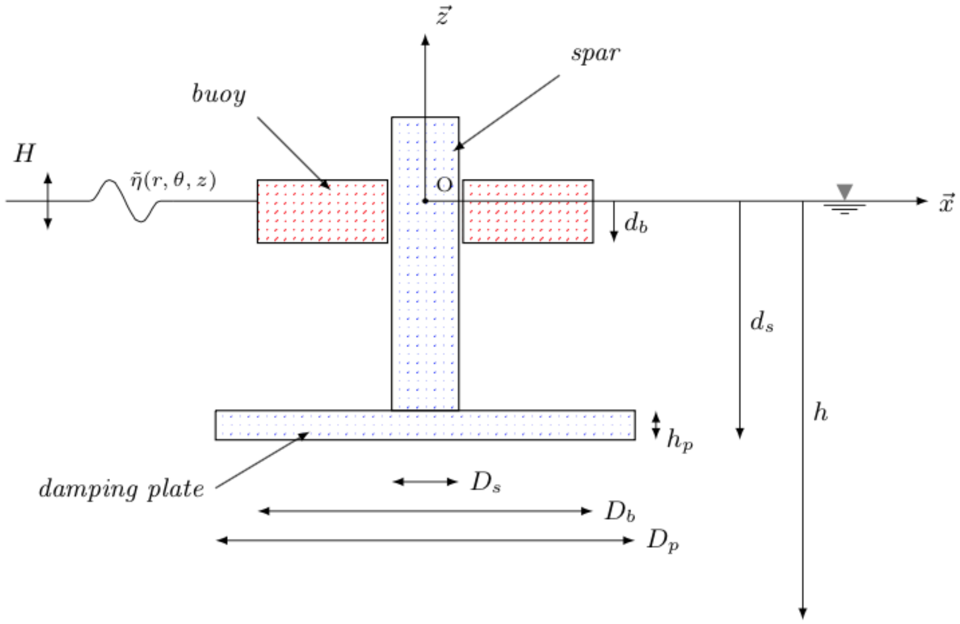


Figure 8: Bobbing Buoy[5]

Each PTO is composed of 4 units of generators. This table shows the characteristics of each permanent magnet synchronous generator:

Power	2400 kW
Connection	4-phase star
Power factor	0.834
Current	667 A per star
Voltage	607 V per star
Velocity	1200 revolutions/min
Frequency	120 Hz
Poles	12

Table 1: Characteristics permanent magnet synchronous generator[25]

The synchronous generator makes the electromechanical conversion, transforming the mechanical energy into electrical energy. This energy must be treated before being injected to the network. In this project, it has been utilized a bidirectional power converter consisting of two conventional pulse-width voltage-source converters. This structure of conversion rectifier-inverter AC/DC-DC/AC is known as back-to-back structure (cf. Figure 9).

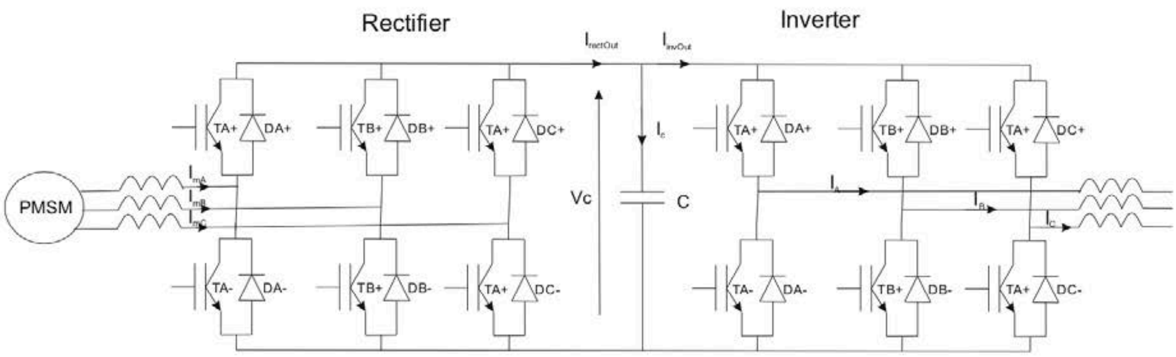


Figure 9: Diagram of the back-to-back structure[26]

It is in this step of the electromechanical conversion chain where the problem of voltage fluctuations takes place. One possible solution to decrease the influence of the voltage fluctuations is to introduce a big capacitor that stores the power. However, considering the dimensions of this project, this solution is not at all recommendable from an economical and a technical point of view. To have an idea about the dimensions of the capacitor needed, we can make a quick estimation, considering that each bobbing buoy produces a power of c. 6 *MW*, the period of the wave might be c. 10 *s*, and the nominal value of the capacitor is 1200 *V*, we would need a capacitor of c. 40 *F*. Even if there exist in the market supercapacitors over 40 *F*, with such value of voltage we would need more than 100 capacitors for each *bilboquet*, which obviously is completely unaffordable from an economic point of view. That is why it has been proposed an alternative solution with the topological disposition of the PTOs in order to limit the influence of the voltage fluctuations.

We can note that in the studies made in the FO Project of the "Lifesaver" they use a ultracapacitor of 4.88 *F* with a nominal voltage of 816 *V*[14], which is much more reasonable than the c. 40 *F* we would need.

3.3 EQUATIONS OF THE SYSTEM

In this section it will be presented a quick overview of the basic equations that affect the system. However, it will not be presented all the development in the calculation of these, neither the basics in the concepts of synchronous machines or power electronics.

- **Equations of the permanent magnet synchronous generator[27]**

The generators work essentially under the principle of Faraday's Law. In this particular case, the rotor has a permanent magnet that rotates following the movement of the wave by the rack-and-pinion mechanism. This rotating magnetic field (changing magnetic flux) generates a voltage in the stator inducing a current that flows through the stator winding. As we are working in three-phase voltage, and considering the effects of the inductances in the variation of the magnetic flux, we arrive to the following expression of the voltage U_i in the phase i :

$$U_a(t) = RI_a(t) + \frac{d\varphi_a}{dt}$$

$$U_b(t) = RI_b(t) + \frac{d\varphi_b}{dt}$$

$$U_c(t) = RI_c(t) + \frac{d\varphi_c}{dt}$$

Where R represents the resistance and φ the magnetic flux in each phase. We can write these 3 equations as a single one, considering the vectors $\boldsymbol{U}=[U_a, U_b, U_c]$, $\boldsymbol{I}=[I_a, I_b, I_c]$, and $\boldsymbol{\Phi}=[\varphi_a, \varphi_b, \varphi_c]$:

$$\boldsymbol{U} = R\boldsymbol{I} + \frac{d\boldsymbol{\Phi}}{dt}$$

If we develop the magnetic flux, $\boldsymbol{\Phi}$, considering the inductance (L) and self-inductance (M) in each phase the same, and we define the synchronous inductance L_s=L-M[2], we arrive to the following expression:

$$\boldsymbol{U} = R\boldsymbol{I} + L_s \frac{d\mathbf{I}}{dt} + \omega \frac{d\boldsymbol{\Phi}_o}{d\theta_e}$$

Equation 3: Equation of the generator in the three-phase frame

Where,

- $\boldsymbol{\Phi}_o = \varphi_o \begin{pmatrix} \cos(\theta_e) \\ \cos\left(\theta_e - \frac{2\pi}{3}\right) \\ \cos\left(\theta_e - \frac{4\pi}{3}\right) \end{pmatrix}$
- $\varphi_o = magnet\ flux\ created\ by\ the\ permanent\ magnets$
- $\theta_e = p\theta_m$
- $\omega = p\Omega$
- $\theta_e = p\theta_m$
- $p = number\ of\ pole\ pairs$
- $\theta_m = angular\ position\ of\ the\ rotor$
- $\Omega = angular\ velocity\ of\ the\ rotor$

However, in order to facilitate the manipulation of the equation that explains the synchronous generator functioning (Equation 3), we can simplify the expression. Under the hypothesis of identical three phases connected to an isolated neutral phase ($i_a(t)+i_b(t)+ i_c(t)=0$) we can change the three-phase system into a two-phase one, hence being able to work in a plane reference frame (*αβ* frame). This transformation consists on a linear application known as Concordia Transformation. Furthermore, to facilitate even more the calculations, we are going to transform the static two-phase reference frame (*dq* frame) into a turning one at the angular velocity ω, which has just been presented. This linear application is called the Park Transformation. We will not enter into detail about this double transformation in this paper, as it is not one of its objectives, so it will just be presented the main concepts and results.

[2] M=-1/2 L, in the synchronous generator, so L_s=3/2 L (cf. [27])

Therefore, if we apply this transformations to the three-phase currents and voltages, $\boldsymbol{U}=[U_a, U_{b,}, U_c\,]$, $\boldsymbol{I}=[I_a, I_{b,}, I_c\,]$, we obtain:

$$\boldsymbol{U_{\alpha\beta}} = \boldsymbol{C_{23}}\boldsymbol{U}$$

$$\boldsymbol{U_{dq}} = \boldsymbol{P}(-\boldsymbol{\theta_e})\boldsymbol{U_{\alpha\beta}}$$

Where:

$$\boldsymbol{C_{23}} = \sqrt{\frac{2}{3}}\begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{pmatrix}$$

Equation 4: Concordia Transformation

$$\boldsymbol{P}(-\boldsymbol{\theta_e}) = \begin{pmatrix} \cos(\theta_e) & \sin(\theta_e) \\ -\sin(\theta_e) & \cos(\theta_e) \end{pmatrix}$$

Equation 5: Park Transformation

And in the dq referential frame, we can express the equivalent to Equation 3 as follows:

$$\boldsymbol{U_{dq}} = R\boldsymbol{I_{dq}} + L_s\frac{d\boldsymbol{I_{dq}}}{dt} + L_s\omega\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\boldsymbol{I_{dq}} + \omega\sqrt{3/2}\,\varphi_o\begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Equation 6: Behavior of the generator in the dq frame

It is important to be familiarized with these transformations, as it turns all the calculation and variable manipulation much manageable, and we will be constantly utilizing these in the following parts. For example, we can see one of these advantages in the case of the torque exerted by the generator, as it depends only on the component on quadrature of the current i_q:

$$\tau = p\sqrt{3/2}\,i_q$$

Equation 7: Torque in the Synchronous Generator

- **Equations of the converters[28]**

The voltage in the terminals of the stator of the synchronous generator has to be controlled to guarantee an adequate behavior of the system. The generator is connected to a three-phase power inverter that allows the control of this voltage. In order to control the power supplied to the generator, it might be used the Pulse Width Modulation (PWM) method, which fixes the duty cycle of the inverter for a given desired voltage. In this section it will be presented the basic equations of the inverter used. However, we will see in the next section that the model proposed is a very simple one, which could be improved by control methods such as the PWM.

Figure 10 shows a diagram of the power inverter connected to the synchronous generator:

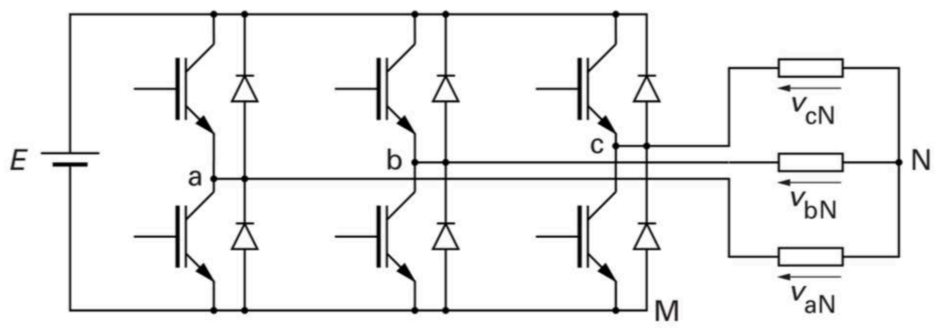


Figure 10: Diagram of power inverter[28]

The study of the equations of this circuit will allow the reader to better understand the behavior of the back-to-back structure presented in Figure 9. If we define the modulation function f_{mi} as f_{mi}=0 if the lower switch of the arm conducts and f_{mi}=1 if the upper switch of the arm conducts, the following matrix represents the relationship between the power source E and each phase's voltage, V_{aN}, V_{bN}, V_{cN}:

$$\begin{pmatrix} V_{aN} \\ V_{bN} \\ V_{cN} \end{pmatrix} = \frac{E}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\begin{pmatrix} f_{ma} \\ f_{mb} \\ f_{mc} \end{pmatrix}$$

Equation 8: Behavior of the power inverter

Chapter 4 SYSTEM MODELING AND CONTROL

In this section it will be described a *Simulink*® model that represents each PTO unit, and we will try to explain each block and the connections between them. As it has already been advanced in the introduction, we were limited to work on the model of one single unit, and not the initial idea of modeling a wave power farm. However, the priority of the project as a whole was to be able to produce a solid model of a *bilboquet* unit, so we dedicated the biggest part of the work in the construction of this model. This first model will be a simplified one (specially the model of the grid), because the first step is to be able to create the adequate structure. Once it has been faced the challenge of the correct design of the model architecture, it will be possible to introduce more complex variables and other possible perturbations.

Some parts (specially the mechanical ones) had already been modeled, so the main challenge was to be able to link each part, uniform the *MATLAB*® script codes and variables, to define the control of the variables, and to be able to find an adequate scale of time common to all the parts (model of the wave, PTO system, power electronics, grid model, etc.). As it represents a very big amount of information, as well as some complex connections between the sub-systems (see Figure 11), we will try to divide the presentation of the whole system into comprehensible sub-parts.

Figure 11 shows the overview of the final model[3]:

[3] For a bigger picture of the model, please refer to 0

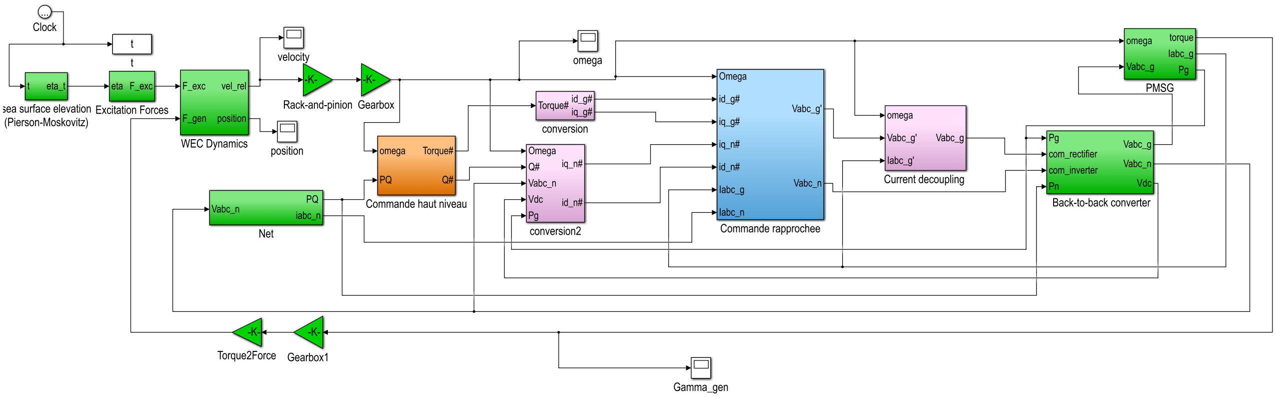


Figure 11: Model of the general system

4.1 MODEL OF THE WAVE SIMULATION AND MECHANICAL SYSTEM

Considering that a partner laboratory elaborated this model and that this paper does not focus on the mechanical system from the point of the view of the wave, we will just present the model and it's place in the general model. For further detail about the mechanical description, refer to the *Laboratoire Brestois de Mécanique et des Systèmes (LBMS)* of the *Ecole Nationale d'Ingénieurs de Brest (ENIB)*, and the references presented in the bibliography at the end[5].

Their task is to develop an adequate mechanic model of the Wave Energy Converter, as well as the study of the waves, their incidence in the WEC, and the behavior of the PTO for a given wave. However, at this point, they have just developed the modeling of a single front of waves and the distribution of energy in frequency by the Pierson-Moskowitz spectra. Therefore, they have calculated how the system must react to one single type of wave, the one simulated, but they have not yet designed a control system for the WEC that reacts to every kind of wave. That is why the block of "*Commande Haut Niveau*" (see Figure 16) just contains two simple gains, for the torque targeted and the reactive power targeted.

Figure 12 presents a scheme where it can be found the different *Simulink*® blocks that generates the simulation of the wave, the force transmitted to the buoy and how the buoy reacts to the excitation forces.

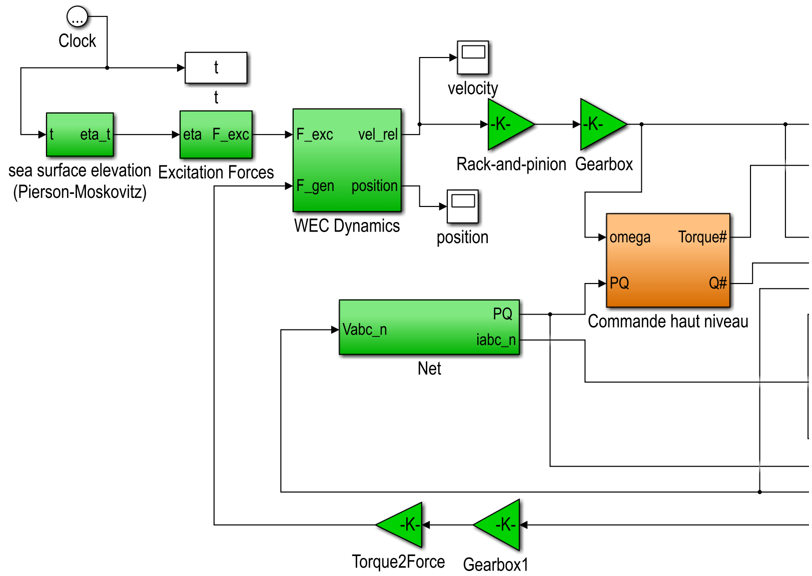


Figure 12: Model of the mechanic part

It will be explained the different blocks:

- **Block Sea Surface Elevation**: this block generates the wave elevation from the variable time. This variable time, t, is created using the *Simulink*® source "clock".

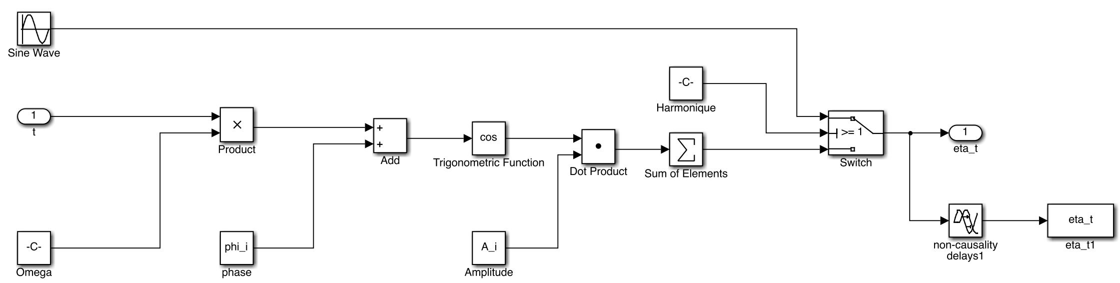


Figure 13: Block Sea Surface Elevation

- **Block excitation forces**: its input is the wave elevation received form the previous block and it calculates the wave excitation force. If we consider

h_{exc} and η, as the impulse response of the wave excitation force related to the geometry of the body, and the wave elevation, respectively, we can present the equation that explains the relationship between the wave elevation and the excitation force in the time domain[5]:

$$f_{exc} = \int_{-\infty}^{\infty} h_{exc}(t-\tau)\eta(0,\tau)d\tau$$

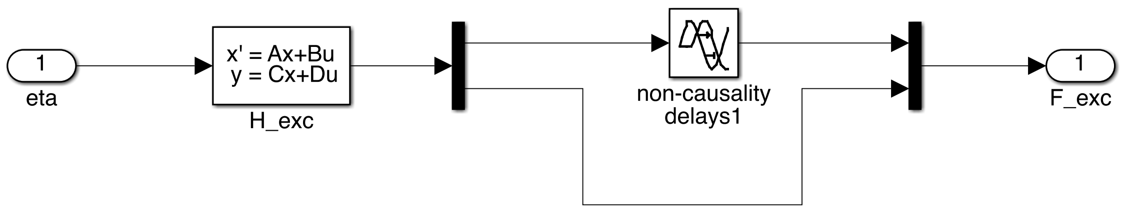


Figure 14: Block Excitation Forces

- **Block WEC Dynamics**: it takes into account the excitation forces of the wave (*input 1* in Figure 15), the force due to the generator (*input 2*), the net restoring force due to gravity and buoyancy (gain "*stiffness*"), and the force due to the radiation problem (gains "*B33_add*", "*K33*", "*A33_inf*"). No further detail of these equations will be provided because of the purposes of this paper. The outputs are the position and the relative velocity of the buoy. Once we have the vertical velocity of the buoy we can easily obtain the angular velocity of the motor using the relation rack-pinion and the gearbox coefficient.

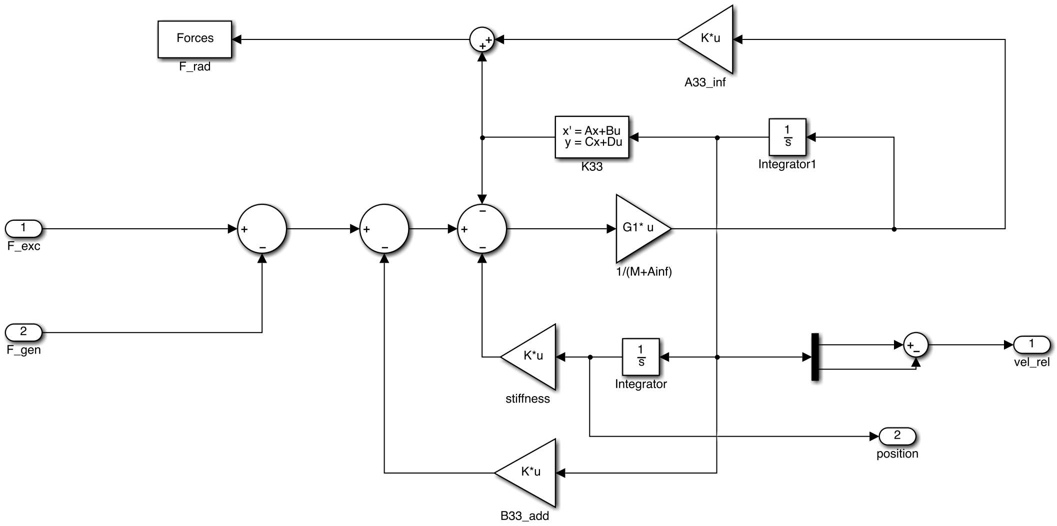


Figure 15: Block WEC Dynamics

- **Block Commande Haut Niveau**: this block is provisionary, as it is only able to manage one kind of wave spectrum. In the future, it is expected to be able to work with every kind of wave spectrum. It takes into account the velocity of the generator and the power requirements of the grid in order to define the targeted torque of the generator and the reactive power to be injected into the network.

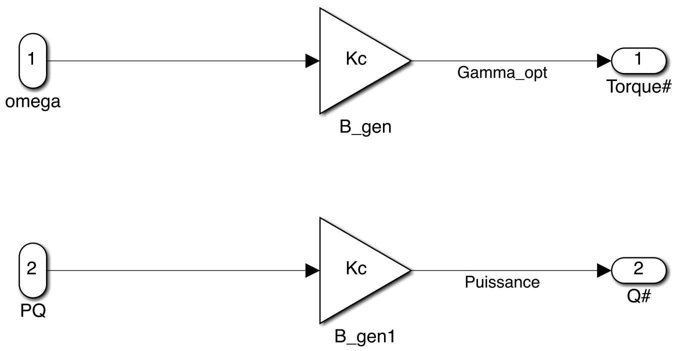


Figure 16: Block Commande Haut Niveau

4.2 MODEL OF THE PERMANENT MAGENT SYNCHRONOUS GENERATOR

This block was the first one conceived, as it is quite easy to manage once we have the equations and the mechanic model of the wave. In order to understand the following systems, refer to the previous section *3.3* where the principal equations were presented, as well as to [27].

Basically, there is a voltage imposed by the power inverter to the terminals of the stator (*Vabc_g* in Figure 17) and an angular velocity of the rotor (*omega*), generating a current (*Iabc_g*), the power generated by the generator (*Pg*) and a resultant torque (*torque*). There are 4 blocks (in orange in Figure 17) that transform the 3-phase reference frame in the dq frame and vice versa and one block (*PMSG_dq*, in green) that translates Equation 6 in a block diagram. About the outputs, it is important to notice that the torque is necessary to drive the WEC Dynamics block presented above, the power of the generator enables the calculation of the bus voltage in the back-to-back structure (see *4.3*), and the resulting current permits the control of the system.

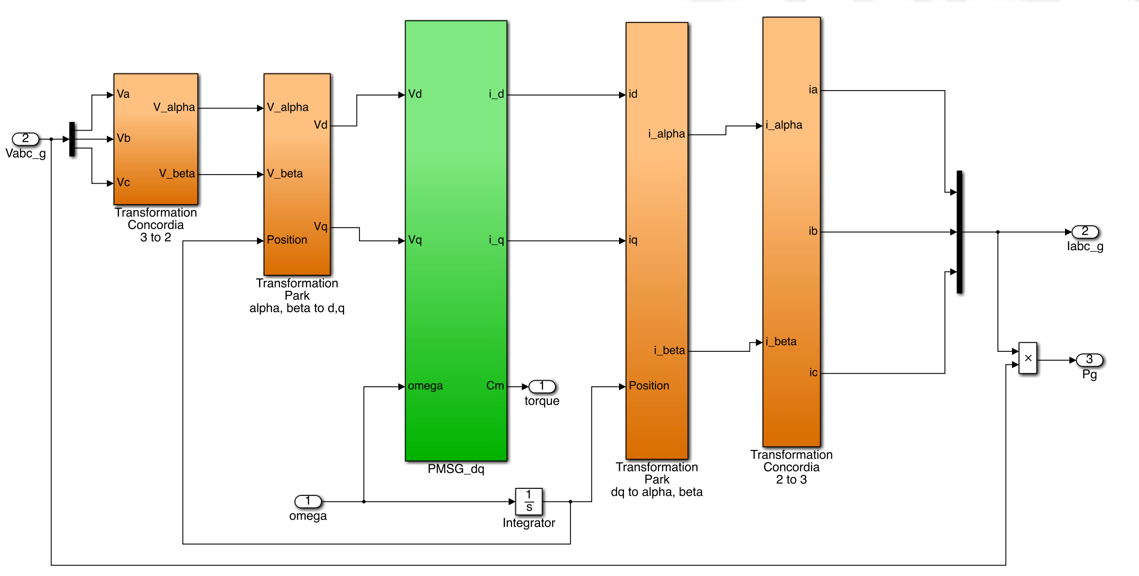


Figure 17: Block PMSG

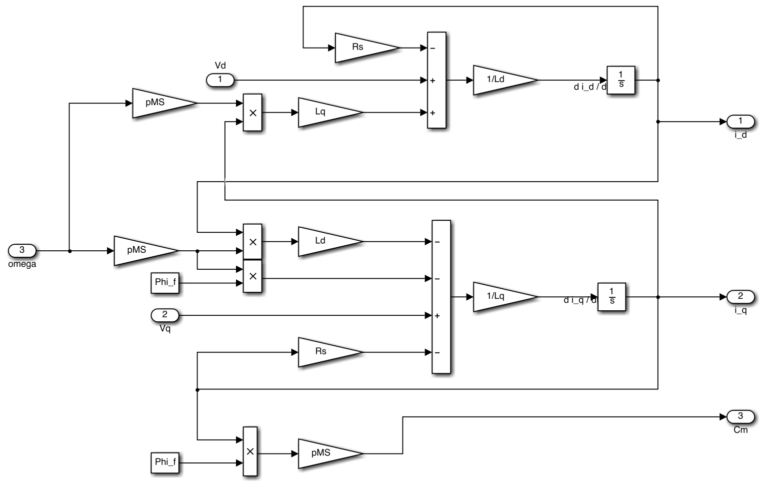


Figure 18: Block PMSG_dq

We will present in this section the blocks of the Concordia Transform and Park transform, that will also appear in other blocks (sometimes the ensemble of this two blocks will be referred as “*Reference Frame Change*”, but it is essentially the same):

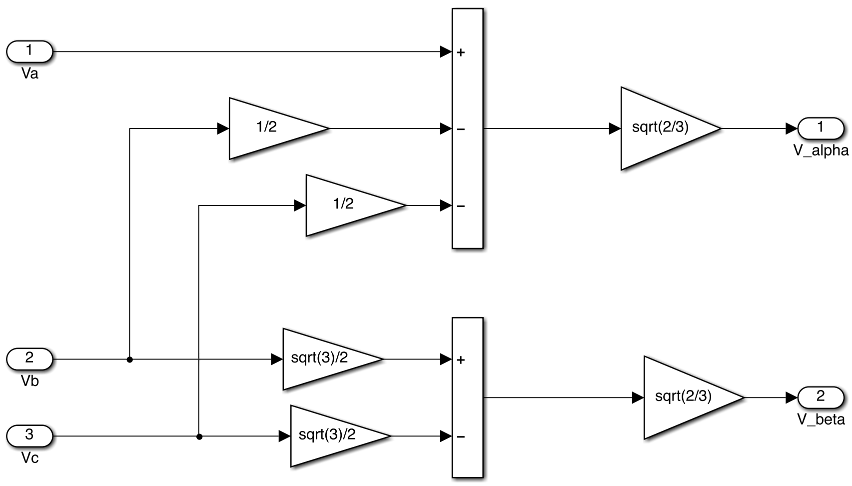


Figure 19: Block Transformation Concordia 3 to 2

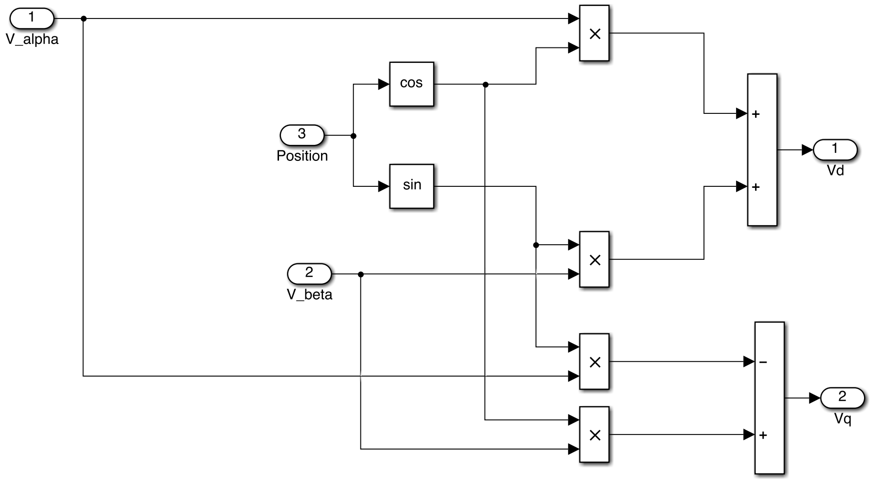


Figure 20: Block Transformation Park alfa, beta to d, q

However, it is important to remark that in order to be able to work with the currents I_d and I_q, and the voltages V_d and V_q independently it is necessary to decouple the currents. To do so, we need to add a compensation block that permits to relate the voltages V_d and V_q to the currents I_d and I_q, respectively, by a single transfer function:

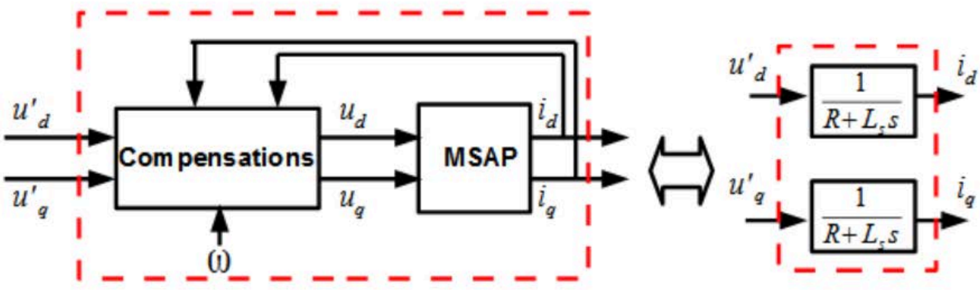


Figure 21: Principle of current decoupling[27]

Here is the implementation of the current decoupling in the block diagram created in *Simulink*®:

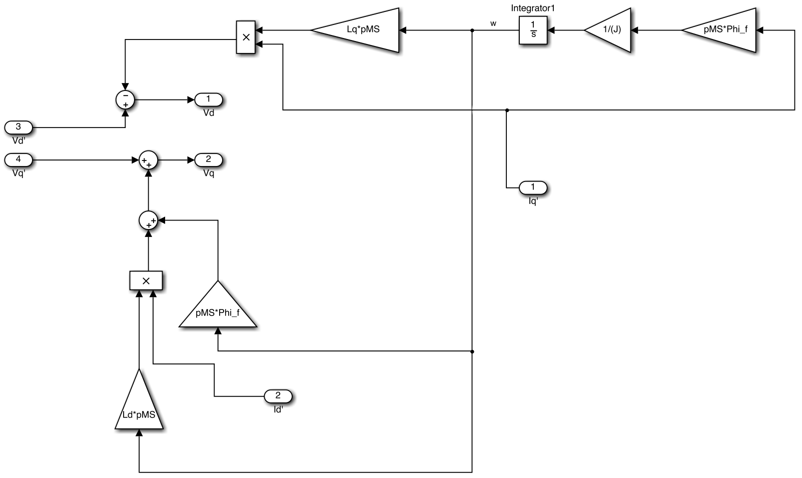


Figure 22: Block Current Decoupling

4.3 MODEL OF THE BACK-TO-BACK STRUCTURE

In the model of the converter, we had to take into account two aspects:

- Firstly, how the inverters affect the voltage in each terminal of the AC/AC converter (the voltage in the terminals of the generator and the voltage in grid terminals). This perturbation is modeled by a simple gain of 1, a time delay (transport delay) and a random signal (converter imperfection and noise). Figure 23 shows the resulting block diagram.

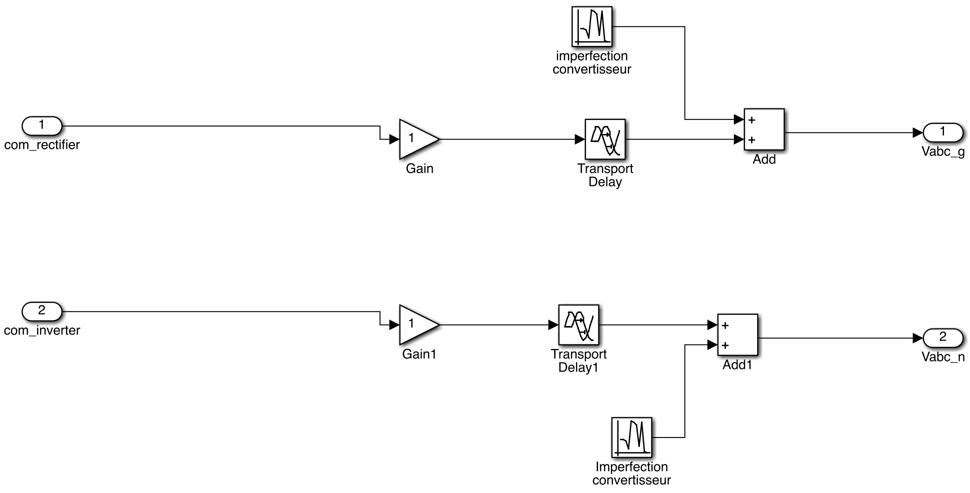


Figure 23: Block Converter control model

- Secondly, the voltage in the bus (V_{DC} in Figure 24) has some limitations (nominal voltage of 1200 *V*[26]) so it needs to be controlled. That is why we need to be able to obtain this voltage somehow, so it can then be controlled with a PID controller (see *4.5*). In order to do so, we measure the power produced by the synchronous generator and the power injected to the grid. We can derive the bus voltage, V_{DC}, by a simple power balance explained in the following equations according to the variables of Figure 24.

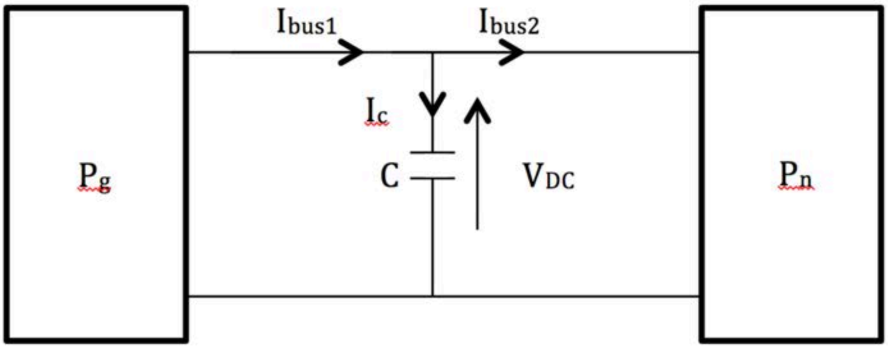


Figure 24: Diagram to calculate the bus voltage

$$Power\ of\ the\ generator = P_g = V_{DC} I_{bus1}$$

$$Power\ of\ the\ net = P_n = V_{DC} I_{bus2}$$

$$I_c = I_{bus1} - I_{bus2}$$

$$I_c = C\frac{dV_{DC}}{dt}$$

$$C\frac{dV_{DC}}{dt} = \frac{P_g}{V_{DC}} - \frac{P_n}{V_{DC}}$$

Equation 9: Calculation of V_{DC} for block diagram

According to these equations, we can understand the model of Figure 25.

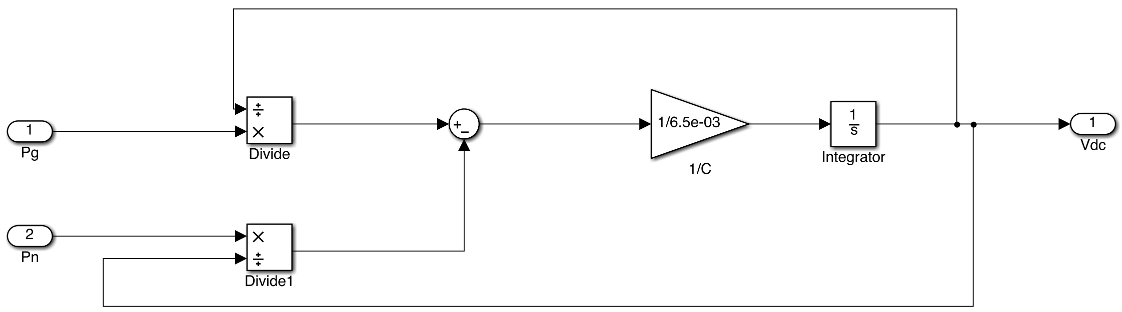


Figure 25: Block Calculation Vdc

Figure 26 shows the resulting blocks that take into account both aspects.

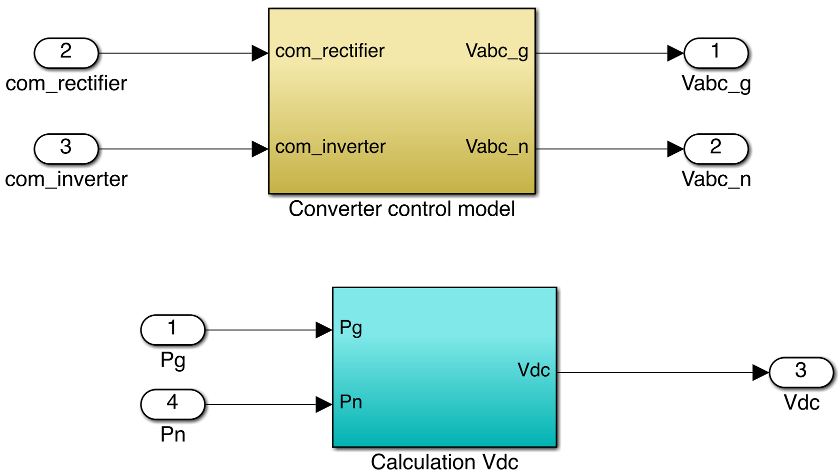


Figure 26: Block Back-to-Back Converter

The outputs of this block will be then:

- The voltage on the terminals of the generator (*Vabc_g*), which will become an input of the block *PMSG*.
- The voltage on the grid side converter (*Vabc_n*), which will be transferred to the block *Net*.
- The voltage of the bus (*Vdc*), in order to be able to control it in the block *Conversion2*.

4.4 MODEL OF THE GRID

The model used for the grid is a very simple one, because as it has been stated, we had to face the first step of modeling the whole structure before taking into account in detail each component. This work is then focused more in finding an overall pertinent architecture rather than the accurate model of each block. Therefore, we will disregard the influence of the transformer, and the losses in wires (*R* and *L* in Figure 27). We will just estimate the value of the voltage on the primary of the transformer (U=640*V*) and then consider the filtering (from the dashed-line in Figure 27 to the left).

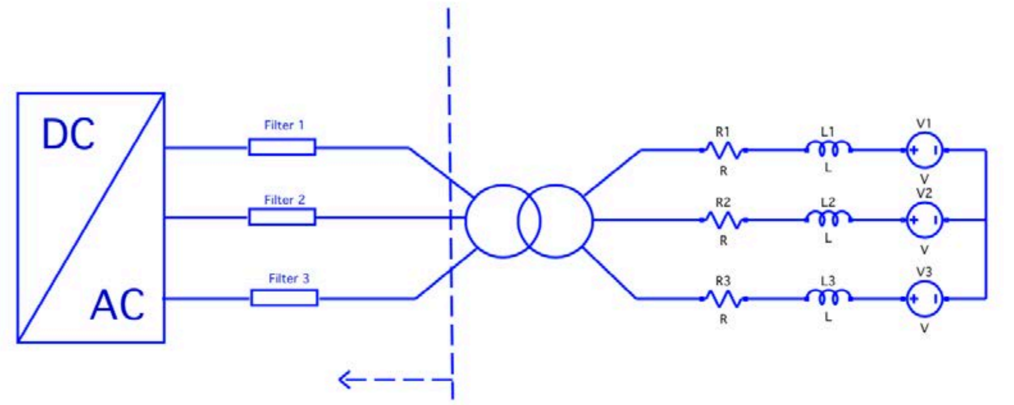


Figure 27: Diagram of the grid

Regarding the filter, we need to design a filter that allows the system to respect the standards for the current flowing into the grid, specially concerning the Total Harmonic Distortion (THD) of the currents. It has been chosen an L filter, a simple but sufficient filter for the aspirations of our model. For a more performing filter, we could have selected an LCL filter in star, but for simplicity of the model the chosen filter is sufficient enough. Figure 28 presents the schematic that will allow us to better understand the equations from which we will derive the block model.

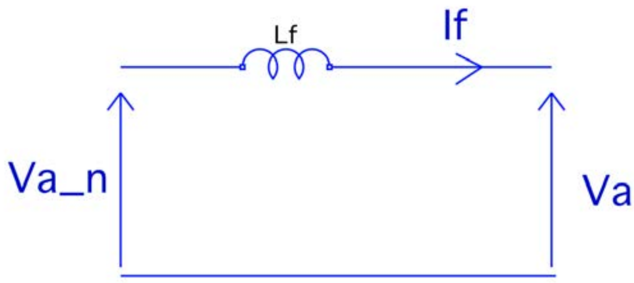


Figure 28: Monophasic equivalent diagram of the filter

Following this diagram, and according to the simplification explained previously (V_a=640/√3 V), for a given voltage at the terminals of the converter (from the grid side), we can easily derive the current I_f from the following equations:

$$V_{an} - V_a = L_f \frac{dI_f}{dt}$$

According to this equation and the research done by the *Laboratoire Ampère*, where they estimated the value of L_f=3.21 mH[26], we can develop the block diagram in Figure 29.

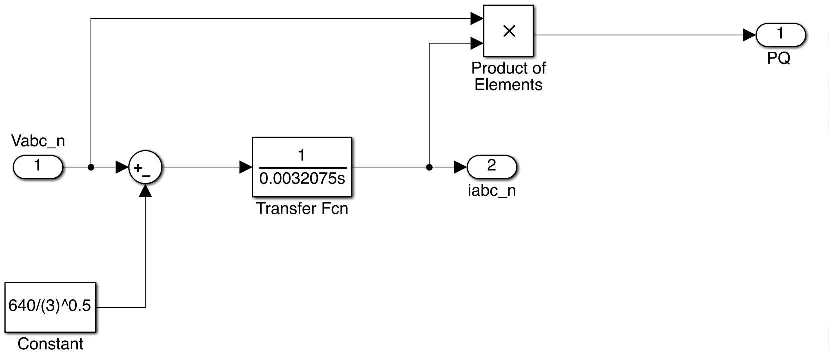


Figure 29: Block Net

4.5 CONTROL

In this part it will be presented the control techniques used to command the unitary system *bilboquet*. First, it will be presented how to obtain the command values of the variables that need to be controlled (blocks *Conversion*) and then the control of these variables (block *Commande raprochée*).

All the command values will be derived from the block *Commande Haut Niveau*, which, is not fully developed yet. This block is expected to be completed by a partner laboratory charged with the mechanical model of the project. It is essential in the final model for the adequate behavior of the system as a whole, as it should be able to define the reference torque (*torque#*) from the state of the sea and the reference reactive power (*Q#*) demanded by the grid. From this block (that now is designed for a given specific wave), all the system control is derived, that is why it is a key component of the system. It is in this block where it has to be defined the control method implemented: latching control, reactive control, etc. For further improvements of the model, it should be reminded that it has been some research about the optimal power extraction that places the reactive control technique as one of the most performing. This technique affirms that the optimal power extraction is reached when the system is controlled with a 90º phase-shift between wave motion and the PTO motion[16].

It has to be decided whether to use a discrete control method or a continuous one. For instance, according to [29], by latching the oscillation during two time intervals of each cycle (a discrete method), the optimal oscillation simply can be approximated. Additionally, it has to be decided if it is better to base the control on the oscillation of the body (like we do in this project) or in the measurement of the wave.

4.5.1 CONTROL OF THE GENERATOR

We can see one of the biggest advantages of using the *dq* reference system in this section, as the reference torque just depends on the quadrature component of the current, i_q (cf. Equation 7). Therefore, we just have to control i_q, so we can define i_d=0 as a reference for the generator. We can easily derive the reference i_{dq} currents from the reference torque. Figure 30 represents these relations.

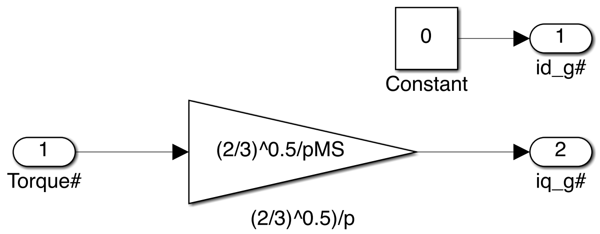


Figure 30: Block conversion

Once we have the reference currents, we can control them with a RST controller, a discrete controller. We will not detail the design of this controller, we will just present the considered constraints in the conception of the controller:

- No stationary error.
- Response time at 5% maximum: 10 *ms*.
- No overshoot.

In addition, we added an "anti-windup" mechanism in order to avoid the integration of the error when the output is saturated. Figure 31 shows the resultant RST controller, for both the i_d and i_q currents of the generator.

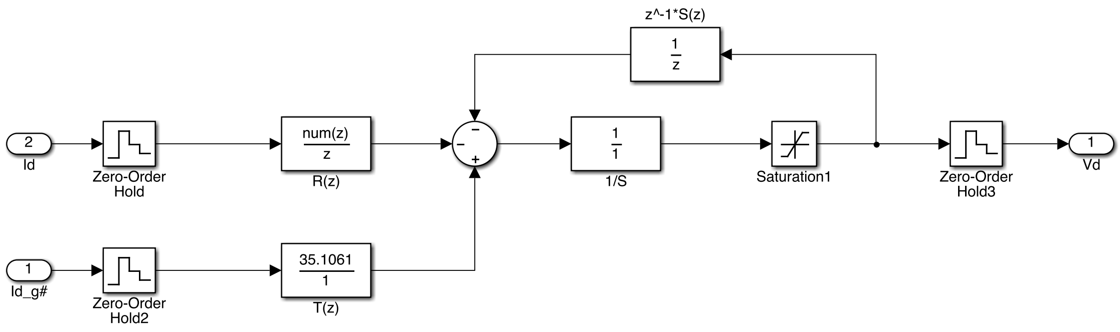


Figure 31: Block Control RST Id_g and Iq_g

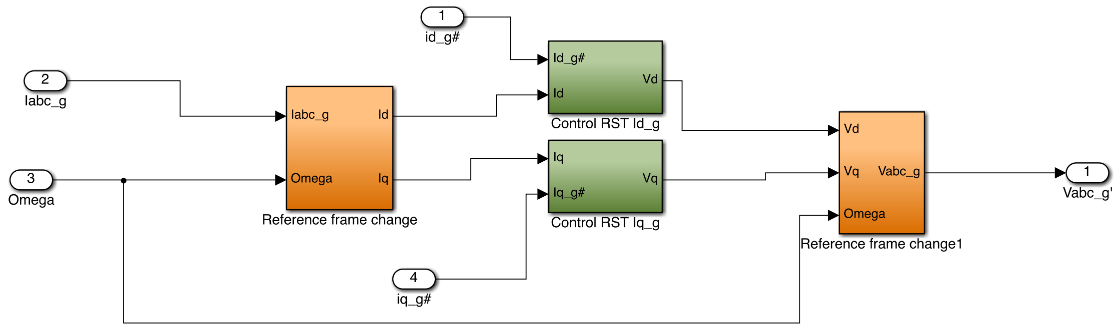


Figure 32: Block Control side generator

4.5.2 GRID-SIDE CONTROL

It will be obtained the reference values for the grid, the command currents i_{dq}#, from the reactive power demanded by the grid *Q#*, and the DC bus voltage. About the reactive power, it is important to understand its relationship with the currents of the converter from the grid-side, and we will see that once more the *dq* reference system is very helpful for the control purposes. We can express the active power, P, and reactive power, Q, in consumer convention by the following equations[26]:

$$P = V_d i_d + V_q i_q$$

$$Q = V_d i_q - V_q i_d$$

But in our control, the reference system is oriented to guarantee that:

$$V_q = 0$$

So

$$Q = V_d i_q \ then \ i_q\# = \frac{Q\#}{V_d}$$

We can then design the blocks in Figure 33.

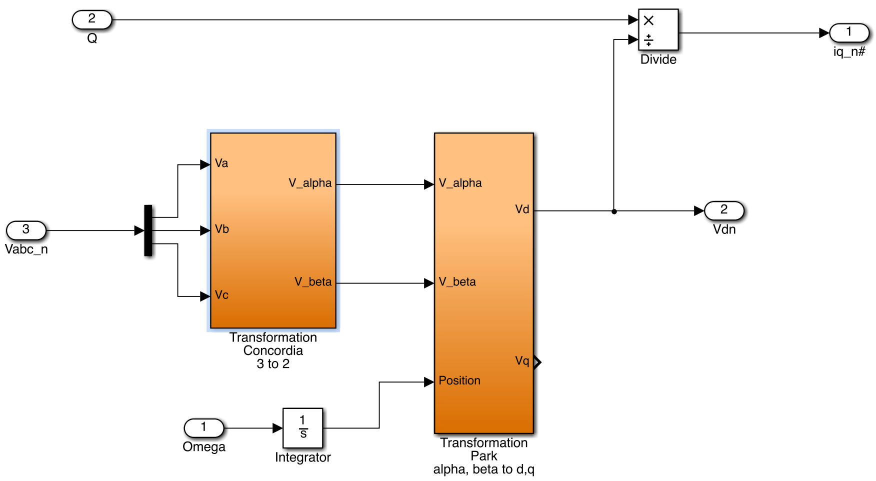


Figure 33: Block Calculation iq_n#

Furthermore, we need to guarantee that the bus voltage is always near the nominal value, so it needs to be controlled too. This fact is traduced in a reference value for the current i_{bus2} (cf. Figure 24), i.e. i_d of the net. Therefore, under the relations between i_{bus1}, i_{bus2}, V_{DC}, and V_d, we can derive the reference value of i_d, of the net, *idn#* in Figure 34. In addition, to control the value of V_{DC} we add a PID controller to stabilize the voltage in the bus to its nominal value V_{DC}=1200 V:

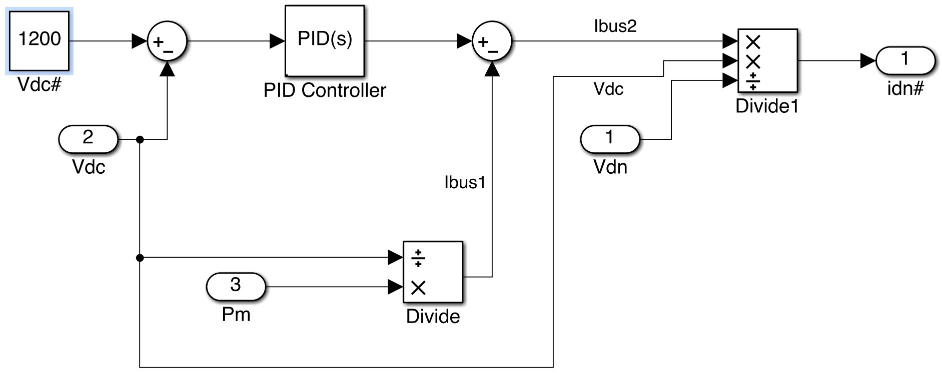


Figure 34: Block Control Vdc

The resulting block that calculates the command currents for the grid is shown in Figure 35.

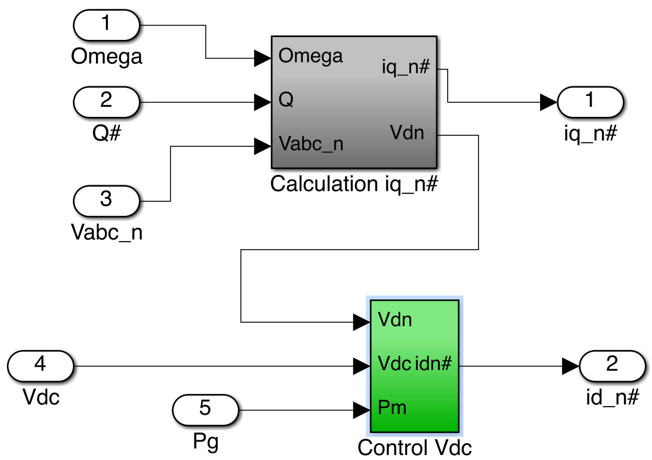


Figure 35: Block Conversion2

However, as we have not developed a very thorough model of the grid, we cannot synthetize an adequate PID or RST controller for the control of these reference currents. We shall remember that the influence of the transformer and the transport grid is completely neglected, so we may just present the general overview that should present this block for further development of the net:

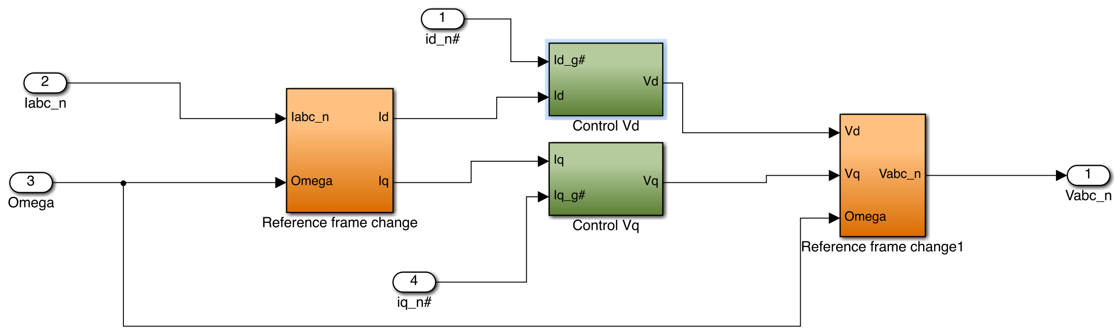


Figure 36: Block Control side net

Finally, the resultant block "*Commande raprochée*" whose function is to control the currents of the converter in both sides, the net and generator side, is shown in Figure 37.

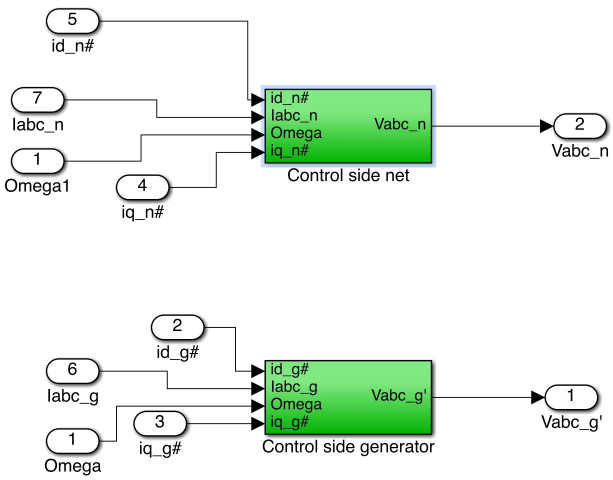


Figure 37: Block Commande Raprochée

4.6 *MODEL VALIDATION AND SIMULATION*

At this point, the only model that has been validated is the ensemble composed of the mechanical part and the synchronous generator. Considering that the model of the grid and all the control part of the voltage in the grid side of the converter needs to be more developed, this validation was the only one that could be representative (because if we used the whole system, the voltage fixed at the terminals of the motor will have no guarantee of being the correct one). Therefore, fixing a constant V_q voltage in the stator's terminals of the generator, we simulate the behavior of this model (see Figure 38).

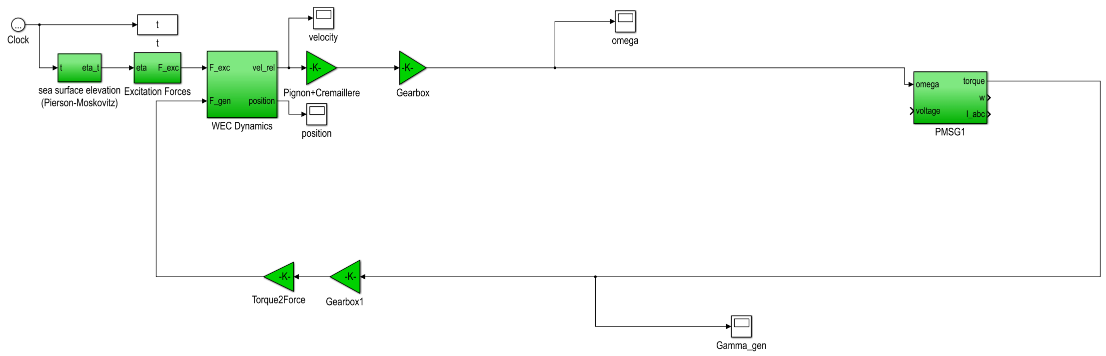


Figure 38: Simplified model of the system for validation

Figure 39, Figure 40Figure 41 are the simulations of the position of the PTO (the vertical and horizontal position), the vertical velocity of the PTO as well as the angular velocity, omega, of the generator in time (180 *s* of simulation).

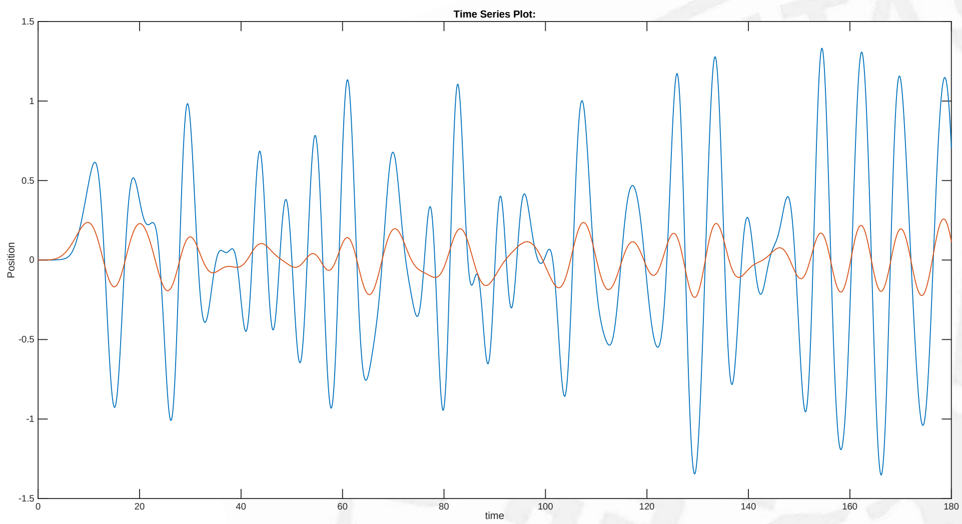


Figure 39: Simulation of the position of the PTO in time

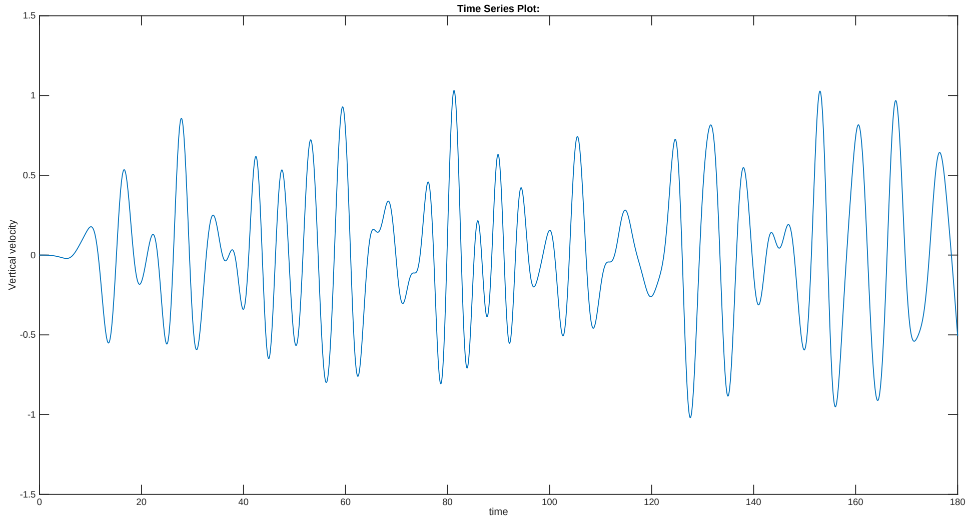


Figure 40: Simulation of the vertical velocity of the PTO in time

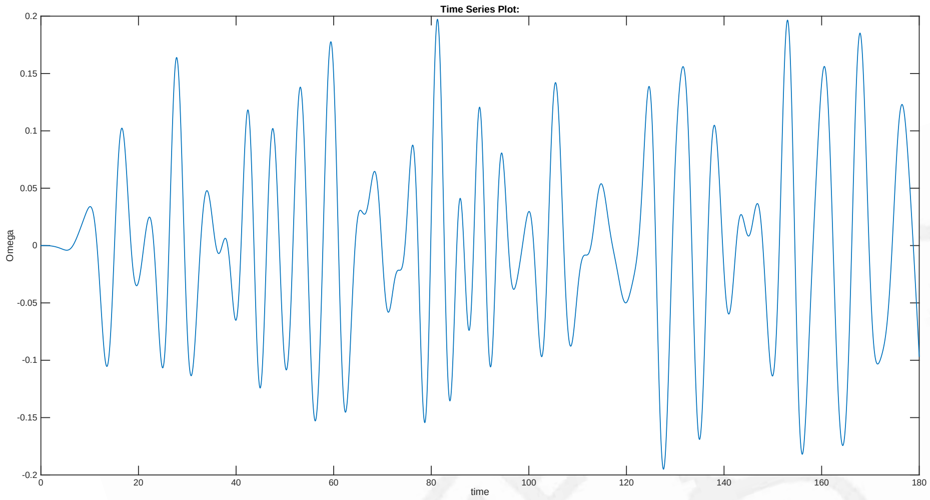


Figure 41: Simulation of the angular velocity of the generator

Chapter 5 CONCLUSIONS AND PERSPECTIVES

The principal objective of this section is to help the reader to get a general overview of the work realized along the development of this project, as well as the results obtained. More importantly, this section should represent the starting point for any further improvement in the development of the wave farm and especially for deeper research on the problem of flicker in this project, focusing on the spatial averaging methods.

This paper has essentially dealt with the presentation of the phenomenon of the flicker, how it directly affects our system, a presentation of the applicable solutions and finally a general model of a unitary bobbing buoy.

Concerning the unitary *bilboquet* model, it is important to reinforce the idea that the main goal of this project was to create the general structure of the model. We could say that this target has successfully been achieved, as it has been presented a model (cf. *Part IIChapter 3*) where all the mechanical and electrical systems are correctly linked, assembled, and ready to be exploited in a simulation.

However, some remarks should be made concerning the level of accuracy and detail of each block:

- The mechanical part, that corresponds to be finished by the partner laboratory of *ENIB*, correctly generates a wave and the motion of the bobbing buoy. However, all the control side, what we call "*Commande Haut Niveau*" in 0, is just designed for that kind of wave front. Therefore, until a more developed control of the mechanical system is designed, no simulations of the flicker mitigation would be relevant enough.
- The model of the permanent magnet synchronous generator is quite an accurate model of the motor, as well as the current decoupling. We might consider adding the inertia of the generator (which is considered in the current decoupling, but not in the model of the PMSG), but it is a

reasonably valid model to proceed with the simulations. The control of the currents of the generator is a priori also valid, but to be verified when simulating the whole system behavior.

- The model of the converter was composed of two parts. Regarding the part of control of the bus voltage and how to obtain it, we could say that it is also fair enough for a valid model to be simulated. However, concerning the power electronics part, a very simplified model was created, with a single gain, a phase shift and a noise signal. This last part may be improved to obtain a more accurate model, or take into account control techniques such as Pulse Width Modulation.
- The model of the grid is clearly the less developed. We just took into account the filter after the converter (which in fact, as presented in *2.3*, it might be omitted with an adequate control technique), and all the influence of the transport losses and the transformer where neglected. Obviously, with such a simple model, there was no interest in designing the control system of the currents of the grid. Therefore, it is quite a rudimentary model that counts on a big degree of potential improvement. In any case, all further incorporations should be added respecting the general architecture of the model, which is still valid.

Finally, looking more in the long term when the problem of the flicker will be dealt with, this paper gives an overview of how this phenomenon concerns the project *Système houlomoteur Bilboquet* and the main measurement techniques. In addition, it was presented the principal solutions in the industry to this matter, and special interest was taken in the spatial averaging solution, which might probably be the best option for our needs. There were also presented some relevant bibliographic references that can represent a useful tool for the application of this technique to this project. Nevertheless, it is important to underline that before trying to implement the exact same solutions for the *bilboquet*, it has to be taken into account the difference in dimensions and performance of our PTO, the *Bilboquet*, and the PTO of the FO Project, the *Lifesaver*.

In conclusion, hopefully this project will not only be a simple research paper with the intention of presenting the curious phenomenon of the Flicker and the system of the *bilboquet*, but it is intended to be a practical tool for the development of this project and the starting point to the following person/group that will try to mitigate the disrupting problem of the flicker in the project *Système houlomoteur Bilboquet.*

BIBLIOGRAPHY

[1] BP, “BP-Statistical Review of world energy 2014 workbook.” 18-Jun-2014.

[2] J. Cruz, Ed., *Ocean wave energy: current status and future prepectives [i.e. perspectives]*. Berlin: Springer, 2008.

[3] Dave Levitan, “Why Wave Power Has Lagged Far Behind as Energy Source by Dave Levitan: Yale Environment 360.” [Online]. Available: http://e360.yale.edu/feature/why_wave_power_has_lagged_far_behind_as_energy_source/2760/. [Accessed: 18-Nov-2014].

[4] Comission “Ressources Energeétiques Marines” du Pôle Mer Bretagne, “Presentation Système Houlomoteur ‘Bilboquet,’” Nantes, 05-Apr-2012.

[5] S. Olaya, J.-M. Bourgeot, and M. Benbouzid, “Modelling and preliminary studies for a self-reacting point absorber WEC,” in *Green Energy, 2014 International Conference on*, 2014, pp. 14–19.

[6] R. O. Ingénieur Senior, EDF Recherche et développement, “Qualité de la Tension - Introduction,” *Tech. Ing.*, Nov. 2002.

[7] R. O. Ingénieur Senior, EDF Recherche et développement, “Qualite de la Tension - Fluctuations et Flicker,” *Tech. Ing.*, Nov. 2002.

[8] J. J. Gutierrez, J. Ruiz, A. Lazkano, and L. A. Leturiondo, “Measurement of Voltage Flicker: Application to Grid-connected Wind Turbines.” University of the Basque Country.

[9] R. Chogllo, R. Isaac, and others, “Análisis de la calidad de energía en el sistema eléctrico, utilizando equipo de medición de parámetros de sistemas fotovoltaicos.” Dpto. Ingeniería Eléctrica, Universidad de Vigo, 2012.

[10] J. Balcells, “Calidad de la red eléctrica: ¿como medirla?” Departement d’Enginyeria Electònica UPC, 2001.

[11] J. Courault and G. de Preville, “Fluctuations de tension et flicker-Evaluation et atténuation (partie 1),” Nov. 2001.

[12] F. Sharkey, E. Bannon, J. MacEnri, K. Gaughan, and M. Conlon, “Voltage Flicker Evaluation for Wave Energy Converters–Assessment Guidelines.” 19-Oct-2012.

[13] K. Gaughan, E. Bannon, M. Conlon, F. Sharkey, and J. MacEnri, “Resource-induced voltage flicker for wave energy converters – assessment tools,” *IET Renew. Power Gener.*, vol. 7, no. 6, pp. 623–630, Nov. 2013.

[14] J. Sjolte, “Marine renewable energy conversion: Grid and off-grid modeling, design and operation,” 2014.

[15] M. Molinas, O. Skjervheim, B. Sørby, P. Andreasen, S. Lundberg, and T. Undeland, “Power smoothing by aggregation of wave energy converters for minimizing electrical energy storage requirements,” in *Proceedings of the 7th European Wave and Tidal Energy Conference*, 2007, pp. 3–8.

[16] J. Sjolte, C. Sandvik, E. Tedeschi, and M. Molinas, “Exploring the Potential for Increased Production from the Wave Energy Converter Lifesaver by Reactive Control,” *Energies*, vol. 6, no. 8, pp. 3706–3733, Jul. 2013.

[17] O. Skjervheim, B. Sorby, and M. Molinas, “Wave energy conversion: all electric power take off for a direct coupled point absorber,” in *Proceedings of the 2nd International Conference on OceanEnergy (ICOE2008), Brest, France*, 2008, pp. 15–17.

[18] J. Sjolte, G. Tjensvoll, and M. Molinas, “Power Collection from Wave Energy Farms,” *Appl. Sci.*, vol. 3, no. 2, pp. 420–436, Apr. 2013.

[19] J. Sjolte, G. Tjensvoll, and M. Molinas, “Self-sustained all-electric wave energy converter system,” *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 33, no. 5, pp. 1705–1721, Aug. 2014.

[20] M. Molinas, O. Skjervheim, P. al Andreasen, T. Undeland, J. Hals, T. Moan, and B. Sorby, “Power electronics as grid interface for actively controlled wave energy converters,” in *Clean Electrical Power, 2007. ICCEP’07. International Conference on*, 2007, pp. 188–195.

[21] J. Sjolte, C. Sandvik, E. Tedeschi, and M. Molinas, "Exploring the Potential for Increased Production from the Wave Energy Converter Lifesaver by Reactive Control," *Energies*, vol. 6, no. 8, pp. 3706–3733, Jul. 2013.

[22] W. Hu, Y. Zhang, Z. Chen, and Y. Hu, "Flicker Mitigation by Speed Control of Permanent Magnet Synchronous Generator Variable-Speed Wind Turbines," *Energies*, vol. 6, no. 8, pp. 3807–3821, Jul. 2013.

[23] Climate Confidential, "offshore_annual_wave_power_level_distribution-ipcc." [Online]. Available: http://climateconfidential.files.wordpress.com/2014/07/offshore_annual_wave_power_level_distribution-ipcc.png. [Accessed: 10-Oct-2014].

[24] "Monochromatic wave." [Online]. Available: http://web.vims.edu/physical/research/TCTutorial/longwaves.htm. [Accessed: 24-Mar-2015].

[25] P. Brutsaert, "Projet Bilboquet-Prototype 9.6MW-Description-Etat d'avancement des travaux-Interfaces," Jeumont Electric, Nov. 2012.

[26] G. Clerc, E. Blanco, and T. Achour, "Modélisation de la chaine de conversion du Bilboquet." Feb-2014.

[27] Laboratoire Ampère, Ecole Centrale de Lyon, "Modélisation d'une machine synchrone à aimants permanents pour aservir son couple." 01-Jul-2014.

[28] Laboratoire Ampère, Ecole Centrale de Lyon, "Modélisation de l'alimentation d'une machine synchrone à aimants permanents." 19-May-2014.

[29] J. Falnes, "Optimum control of oscillation of wave-energy converters." Institutt for fysikk, NTH, Jun-1993.

Part II APPENDIX

Chapter 1 LIST OF PARTNER LABORATORIES AND INSTITUTIONS

- ***d2m*** is an naval architecture institution of about 80 people, members of *Pôle mer*, that works on the civil and military naval domain, as well as the offshore industry and the renewable maritime energies
- ***CMD Engrenages et Réducteurs*** is one of the world leaders in the power transmission for the heavy industry. It employs 400 people, essentially in their Cambrai site, France.
- ***CervVal*** is an institution of around 10 people, member of the *Pôle mer*; it is founded under the technologies developed by the *Centre Européen de Réalité Virtuel (CERV)*, that exploits algorithms for Virtual Reality applications and they apply them in domains such as numerical simulations of physical phenomena.
- ***Adetel*** conceives, develops, industrializes and fabricates electronic equipment and software for severe, embarked or limited industrial environments. The group employs 500 people in the Rhône Alpes, France.
- ***Ifremer*** contributes, by their work and experts to the knowledge of oceans and their resources, to the protection of the sea medium and the sustainable development of maritime activities.
- ***Jeumont Electric*** is one of the main constructors of generator of high performance.
- ***Oceanide*** is specialized in the development of projects in the maritime domain. The institution employs 17 people and is member of the *Pôle mer*.
- ***Bureau Veritas*** is an international group of 40 000 people, specialized in the inspection, analysis, audit and certification of products, infrastructures (buildings, industrial sites, equipment, etc.) and management systems (ISO norms, etc.) according to regulatory or voluntary constraints. Its Marine

division provides classification services and it is also member of the *Pôle mer*.

- ***ENIB (Ecole National d'Ingénieurs de Brest)*** regroups permanent researchers/teachers, in a laboratory with research studies about the non-linear control of systems. The applications are about the development of actuators with adaptive materials and the control of electric motors.
- ***Laboratoire Ampère (Université Claude Bernard)*** is a laboratory that develops algorithms and control laws for the generators.

Chapter 2 MODEL OF THE FLICKERMETER

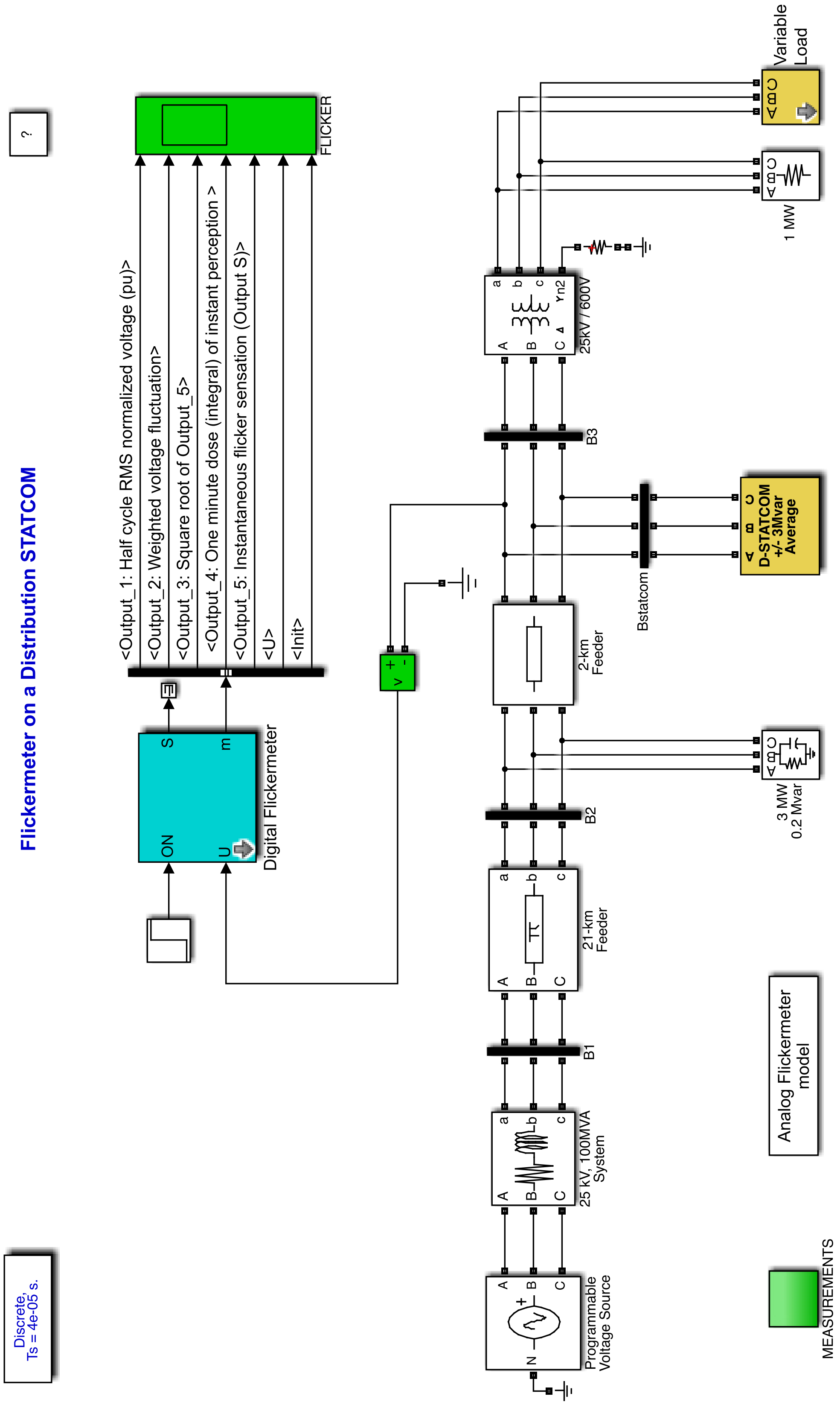


Figure 42: Standard Flickermeter

Chapter 3 MODEL OF THE SYSTEM

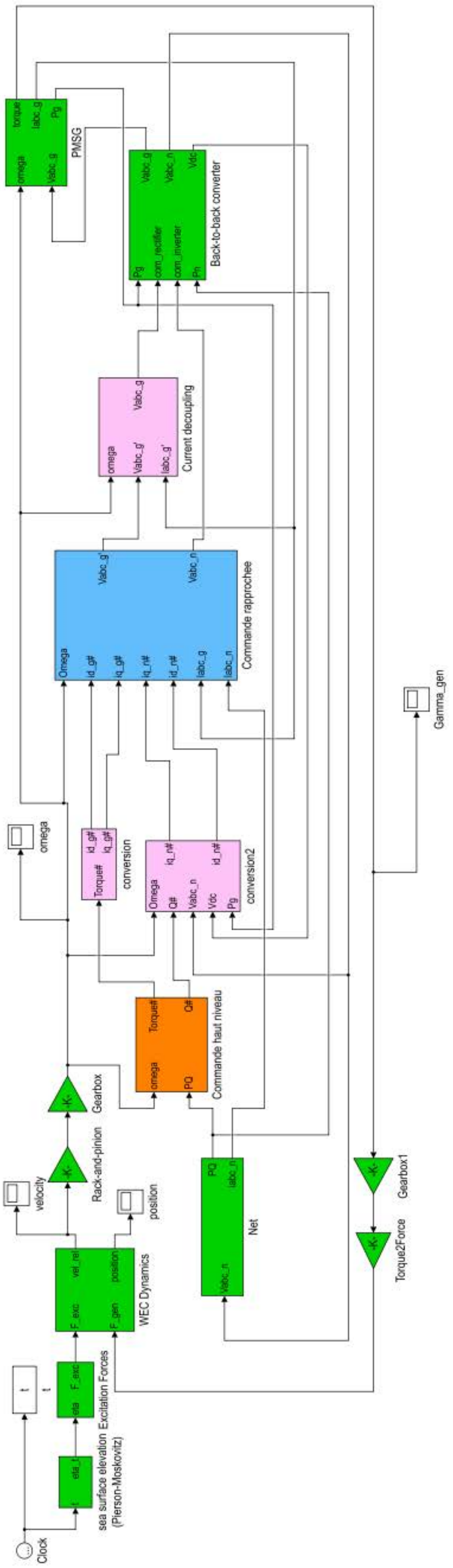


Figure 43: Model of the general system
(big image)