High Voltage Shore Connections
Application in piers and power supply ships

Final Bachelor's Degree Project

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Thanks to my parents, my family, my friends, my teachers and to everyone who has stood with me all this time. Thanks for your invaluable help, your support and your confidence in every possible situation. Thanks for never stop believing in me.

Abstract

The High-Voltage Shore Connections (HVSC) are an efficient way to reduce air pollution in ports and its surroundings, as it allows ships to connect themselves to a shore source of energy and shut down their engines, thus cutting their contaminant emissions. To be able to carry out this connection between the shore electrical grid and the ship, it must be taken into account that, generally, both systems work with different voltages and frequencies. Therefore, the HVSC must be in charge of not only transmitting energy from piers to ship and vice versa, but also doing the suitable conversions so that the two networks may connect each other properly. In this project, it is designed and analyzed a possible solution of the circuit in charge of making these energy transformations.

After completing the design of the system, simulations under different load situations and possible failures are run. With four ships using in parallel the HVSC, it may be seen, besides the regular behavior of the circuit, the repercussions and effects in the whole system when a short circuit takes place in one of the connecting electric feeders between one of the ships and the converter system. Similarly, also the effects of one step in the energy required by a ship (an increase or decrease of 1 MVA, regarding the 5-10 MVA that it regularly needs) in the rest of the circuit can be observed.

Both the design of the circuit and the conditions of the simulations are performed with Matlab Simulink, and the results are compared with stablished requirements by international regulation associations. In this case, Classification Societies, who are normally the main references when introducing normative and requirements in the maritime ambit, stablish few regulations about it. Instead, the International Standard ISO/IEC/IEEE 80005-1 covers with detail all the subject about harbor connections, on the ship side as well as on the shore side. That is why this Standard is the one that will be taken into account to observe the system operation limits.

The results show that in case of short circuit in one electric feeder, the voltage goes down to zero, while the current goes up to very high values, as it was expected; this causes transient changes in the voltages and currents of other feeders, which includes peaks in the electric feeder going directly to a ship. Meanwhile, in the cases of increase and decrease of the loads it is observed that when the load of one ship is increased, the voltage in its feeder decreases and the current grows, and the opposite happens when the load is decreased. With the load variation simulated, the effects of these load changes are barely noticeable in other ships, except for the ship supplied directly from the source, where a little variation appears in voltage.

Therefore, it can be concluded that even most of studied cases don't cause severe alterations, there are some exceptions. On one hand, a short circuit in the source electric feeder affects importantly to the rest of the feeders. And on the other hand, it must be taken into account that the load change in one feeder will affect to the voltage supplied, being deviated from the nominal voltage stablished by the rule.

Resumen

Las conexiones de puerto de alta tensión (HVSC) son una forma eficiente de reducir la contaminación ambiental en los puertos y sus alrededores, ya que permite a los buques conectarse a una fuente de energía en el muelle y apagar los motores, reduciendo así sus emisiones contaminantes. Para poder llevar a cabo esta conexión entre la red eléctrica en tierra y la propia del barco, debe tenerse en cuenta que, por norma general, ambos sistemas trabajan a tensiones y frecuencias diferentes. Por lo tanto, las HVSC deben encargarse no solo de transmitir la energía desde el puerto al buque y viceversa, sino también de efectuar las conversiones necesarias para que las dos redes puedan estar conectadas sin sufrir problemas. En este proyecto se diseña y estudia precisamente una possible solución del circuito que ha de llevar a cabo esas transformaciones de energía, adaptando la tensión generada por la fuente a una que sea adecuada para la red del buque usando la conexión.

Tras completar el diseño del sistema, este se pone a prueba, simulando distintas situaciones de carga y posibles fallos. Con cuatro buques usando en paralelo la HVSC se ven, además del comportamiento normal del circuito, las repercusiones que tendría un cortocircuito en las líneas de conexión entre uno de los buques y el sistema de la conversión en la energía que llega a los demás buques. De igual forma, también se observan los efectos de un escalón en la energía requerida por un buque (un incremento o disminución de 1 MVA, respecto a los 5-10 MVA que puede necesitar normalmente) en el resto del circuito.

Tanto el diseño del circuito como las simulaciones de las condiciones se llevan a cabo con el programa Matlab Simulink, y los resultados son comparados con los requisitos establecidos por las asociaciones internacionales de regulación. En este caso las Sociedades de Clasificación, normalmente las mayores referencias a la hora de introducir normativas y requisitos en el ámbito marítimo, establecen muy pocas regulaciones al respecto. En cambio, el Standard Internacional ISO/IEC/IEEE 80005-1 cubre detalladamente todo el tema de conexiones en puertos, tanto en el lado del buque como en el de tierra, por lo que se atenderá a este para observar los límites de operación del sistema.

Los resultados muestran que en el caso del cortocircuito en una línea, la tensión baja hasta cero mientras la corriente sube a valores muy altos, como era predecible; esto provoca alteraciones transitorias en las tensiones y corrientes de las otras líneas, incluyendo picos en la línea que alimenta directamente a un buque. Mientras tanto, para los casos de aumento y disminución de carga se observa que cuando se aumenta la carga de un buque, la tensión en esa línea baja mientras la corriente sube, y al revés cuando se disminuye la carga. Con la variación de carga probada, los efectos de estos cambios de carga son apenas perceptibles en los otros buques, a excepción del buque alimentado directamente de la fuente, donde aparece una pequeña variación en la tensión.

Por lo tanto, se puede concluir que aunque la mayoría de casos estudiados no provocan alteraciones muy graves, hay ciertas excepciones. Por un lado, el cortocircuito en la línea de la fuente, que afecta de forma muy importante a todas las demás líneas. Y por el otro, debe tenerse en cuenta que el cambio de carga en una línea afectará a la tensión que va a recibir, lo que la hará desviarse de la tensión nominal establecida por la norma.

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1. Introduction

Nowadays, many plans against air pollution are being implemented all over the world. Being aware of the dangers and the effects of the global warming, increasing year after year, every time more restrictions related to the emission of polluting elements are being introduced. This contamination is mainly produced by the combustion of hydrocarbons that takes place inside engines, and for this reason is very important to regulate them, and also to reduce their use always as possible.

When trying to decrease the pollution in cities located next to big ports, this subject becomes an even harder issue. Big ships mean big engines, and they are a huge source of contaminant emissions. When a ship is berthed at dock and has its generators working to provide the energy that it needs, the pollution generated affects directly to the air quality and the health of the inhabitants living close to the port.

For example, a big cruise ship which uses 11 MVA to supply all its systems, consumes the equivalent energy of more than 2,700 houses, taking as a reference the electrical average power of a house in Spain (4 kW, as the electrical power of an average size house is between 3.45 and 4.6 kW). In a place like the Barcelona’s harbor, capable of hosting up to nine cruises at the same time, it is clear that it will represent a significant negative effect on the environment.

This is the reason why alternative sources to obtain the energy that a ship needs at berth are being searched. To utilize a High Voltage Shore Connection (HVSC) is a great possible solution: it is based on connecting the ship to an external electrical grid, allowing turning off the ship’s engines. As a result of this practice, the ship’s emission of polluting gases can be completely avoided.

The above mentioned is one of the primary uses of the HVSC, although it is not the only one. A High Voltage Shore Connection may be used also in the opposite direction. Instead of connecting the shore to the ship to provide it with the energy needed, it is possible to use this connection to provide energy to the electrical grid.

This option might be considered in case of a shutdown of the electrical grid, or in a situation that requires a special electrical alimentation. The shutdown could be caused by a natural catastrophe, an accident or any other problem that could harm the generation of electricity, while the special alimentation could be due to any occasion that needs an unusual demand. In this case, the electricity should be provided by an off-shore platform or a supply ship capable of generating energy in its own, independent way. When needed, this ship or platform could be approached to the shore, then connected through a HVSC to the electrical grid, and finally provide the required electricity.

Actually, many important ports worldwide are introducing technologies such as these High Voltage Shore Connections: Port of Los Angeles (USA’s largest container port) was one of the pioneers, and other examples may be found in the Gothenburg Port and in Antwerp Port. This is being done in order to try to reduce and eliminate the emissions of ships and to benefit from the advantages that this technology offers. That is why it is interesting to study this system, analyze how it works and evaluate its performance under different conditions and unexpected perturbations.

1.1. Objectives

As it has been stated, the High Voltage Shore Connections are a vital element for the technology development in ports, as well as useful in special conditions of energetic needs. Therefore, the aim of this project is to study their application in harbors and power supply ships. This can be divided into the following objectives:

- To identify the applicable rules and directives, consulting the IEC, UNE and IEEE Rules. The Rules of the Classification Societies will also be investigated.
- To study the High Voltage Shore Connections deeply, analyzing how they work and identifying their main components.
- To design and simulate the electrical circuit that will allow the HVSC to carry out efficiently their task, using Matlab Simulink.
- To study and analyze the behavior of the whole electrical system under different load conditions and in unexpected faults conditions, analyzing how these perturbations affect to the stability of the circuit.

1.2. Motivations

The Final Degree Project is the last work that must be done to become officially an engineer, so it is obvious that the process of developing it is a very important matter in the life of any Engineering student. The part of choosing the subject of the Project is also vital, because this work will be the main priority of the student for at least four months. As a result, the idea of the Project must be attractive enough to ensure that the student will not get bored or frustrated, even in the toughest moments of the Project.

In my personal situation, I had known for a long time that I wanted to do my Project about something related to the environment, in one way or another. It is a topic I have always been concerned, and I have done works about it during all my life, not only at the university. Other point that I had clear was that I did not want to do a completely and long theoretical Project, but a work with a strong practical part from which I could learn and where to apply what I have studied.

With that stated, it was my tutor who suggested the subject for this Project. The High Voltage Shore Connections are not something directly related to the environment, although it is a fact that their implementation could avoid a lot of contaminant emissions from ships that would affect to the environmental conditions. Moreover, it was a topic that would help me to expand my knowledge, and not just about the High Voltage Shore Connections themselves.

On one hand, the electrical subjects have never been the ones to which I have paid the most attention during all my Degree. There were too many lectures and too much work to do in all classes, and I could never focus on these ones. The main electric basis of the Project would help me to solve this, and I could finally concentrate in learning and improving what I know about electricity and power.

On the other hand, this Project offered me the possibility to work with Matlab Simulink. Even knowing that it is a really useful and important tool in the engineering world, before the Project I had had only a few chances to use it. This is why the perspective of improving my skills with the program was another positive point of realizing the Project.

Finally, this Project is about finding a solution and analyzing its suitability and response to changing conditions. That is what I have always wanted to do: to design something to solve a problem and to know that it will perform well.

1.3. Methodology and sources

The sources consulted for developing this Project have been mainly electrical publications, papers from universities and documents of electrical companies. Also, other Final Degree Projects with similar topics have been studied.

Other documents have also been consulted as a support, such as some UNE Rules. The Rules of a few Classification Societies have been observed, as well as IEC/ISO/IEEE International Standards, as they have strict regulations concerning electrical systems that must be followed and taken into account.

Moreover, Matlab manuals have been very useful to understand better how the program works and to help with the design phase. Class books about electricity and electronics have been a good support to understand how each part of the system performs.

Concerning to the methodology of the Project, it has been based on learning about the High Voltage Shore Connections, understanding their operation and analyzing all the elements that conform them, while in the other side becoming familiar to the Matlab Simulink style of work.

After that, the process has consisted of designing the circuit of a High Voltage Shore Connection, part by part. And once the initial design has been finished, the objective has been to analyze the behavior of the system with different load conditions, unexpected problems and even changing situations.

2. Shore power connections

As it has been stated, the High-Voltage Shore Connections are the elements who link the electrical system of a ship (or any other floating artifact) to the harbor's grid. It is important to notice that this kind of connection is called with a range of different names depending on the rules, the country or the classification society that it is consulted. As well as the name of High-Voltage Shore Connections (HVSC), the following are also used:

- Shore-side Electricity
- Electrical Shore Connections
- On-shore Power Supplies
- Cold Ironing

2.1. Description

The arrangement of a typical HVSC system can be seen in the next figure, shown as a block diagram of the basic hardware elements:

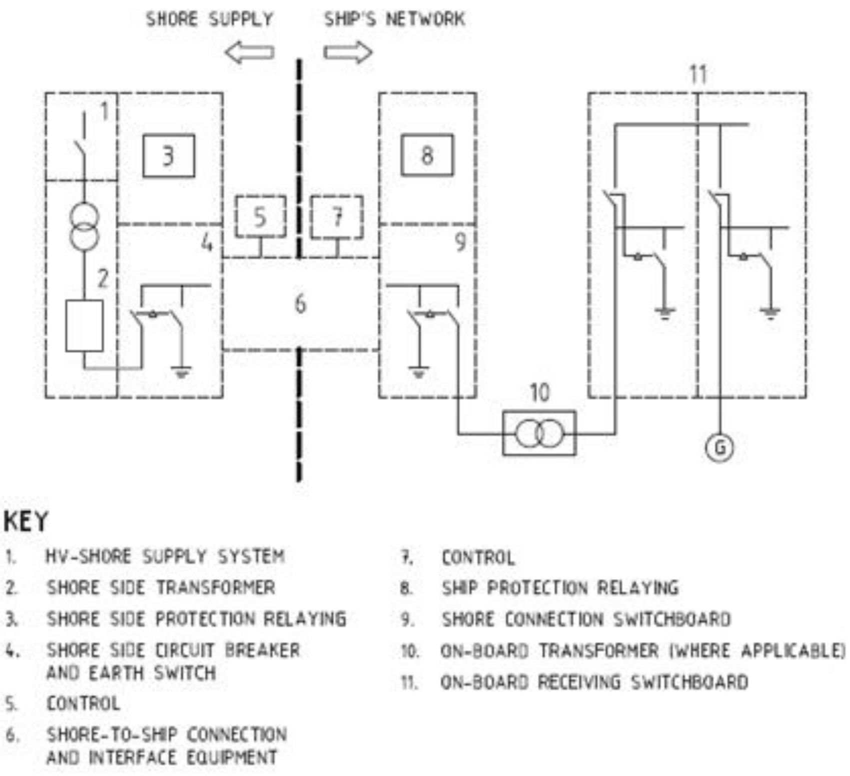

Figure 1: Block diagram of the HVSC system [2]

The system may be split in two big blocks: on the left side, there is the Shore Supply, formed by the elements installed at port; while on the right side can be found the Ship's Network, where are represented the components that are placed on board.

This project is focused on the circuit of the Shore Supply side, and that is why only this part will be analyzed. While the Ship's part is widely studied and regulated by many Classification Societies and ISO Rules, the Shore part obtains much less attention, being regulated only by a few standards of electrical commissions. Even though, it has a series of safety and quality requirements that must be fulfilled, which will be later analyzed.

The blocks located on the side of Shore Supply are:

- The block number 1 is the High Voltage-Shore Supply System. This block is the one that takes the electricity from the national grid, the generator of the port's energy or any other source of power, so it can be transformed and transferred to the ship that needs this energy.
- The block number 2 contains the transformer, besides the power-electronic conversion system. This is used to transform the power coming from the supply system in order to be admissible by the ship. While the energy supplied by the system has its own voltage, the ship's network also operates with its particular voltage, different from the one of the supply system, and this block must be ready to solve this issue.
- Block number 3 is the protection relaying. This element is truly important in terms of safety, as it protects the system from any damage in case of failure, overload or short circuit.
- Block number 4 consists of the circuit breaker and earth switch, which is used to connect and disconnect the shore supply system to the interface that joins it to the ship's network, as well as increases the safety of the circuit.
- The block number 5 is the control. From this one the parameters, breakers and connections of the supply circuit can be monitored and changed.
- Finally, the last block to be considered is number 6, formed by the shore-to-ship connection and the interface equipment. This one consists of the wiring that links both electrical systems from port and ship, and includes all the elements attached to the cables and used to maintain united the connection.

All this equipment is used to receive the energy from a supply system, whatever it is, and to treat it so it can be transferred to the ship with the voltage and frequency its network needs. The process of the transformation of the electricity's conditions is the one that is going to be designed and simulated in further chapters.

In fact, some aspects of the possible installation of a HVSC in a place such as the Port of Barcelona have already been studied in another Project **[3]**. In this one, it will be looked further into the design and simulation parts of the process.

2.2. Reasons for using them

There are many reasons for using the High Voltage Shore Connections in harbors of all over the world. The most obvious one, already mentioned, is the fact that it is a way to reduce air pollution in the port and its surroundings, although it is not the only one. Other reasons are the reduction of the noise that switched on engines and generators create, the possibility of perform maintenance activities in the engines, to have modern and improved harbor's facilities, and even to make an economic save.

The main reason is that it is a technology that reduces the ship's emissions while they are berthed, and it is a very important matter. According to a study, ship's polluting emissions contribute in almost 60,000 deaths per year in the entire globe **[4]**, and affect to the health of a much higher number of people. And besides the health issue, there is the fact that every time more rules and regulations related to ship's emissions are being approved. The most important producer of these regulations is the International Maritime Organization (IMO), who through its resolutions, circular letters, working committees and MARPOL annexes introduces gradually more restrictively laws affecting the emissions, as well as recommendations and proposals in the same subject.

Aside from the IMO, other regulation authorities such as local governments, the EU Council, USA or the United Nations, have presented different rules, initiatives, proposals, common points of view and other legislation acts regarding the air contamination produced by ships. For example, the European Union published a recommendation advocating for the use of Shore-side power in 2006 **[5]**, and it is also promoted by associations such as the World Port Climate Initiatives (WPCI) or the International Network of Port Cities (AIVP).

And while ships are one of the biggest sources of air pollution (they are responsible of 2% of CO_2, 15% of NO_x and 6% of SO_x global emissions **[6]**), the electricity generated on land releases considerably lower harmful emissions:

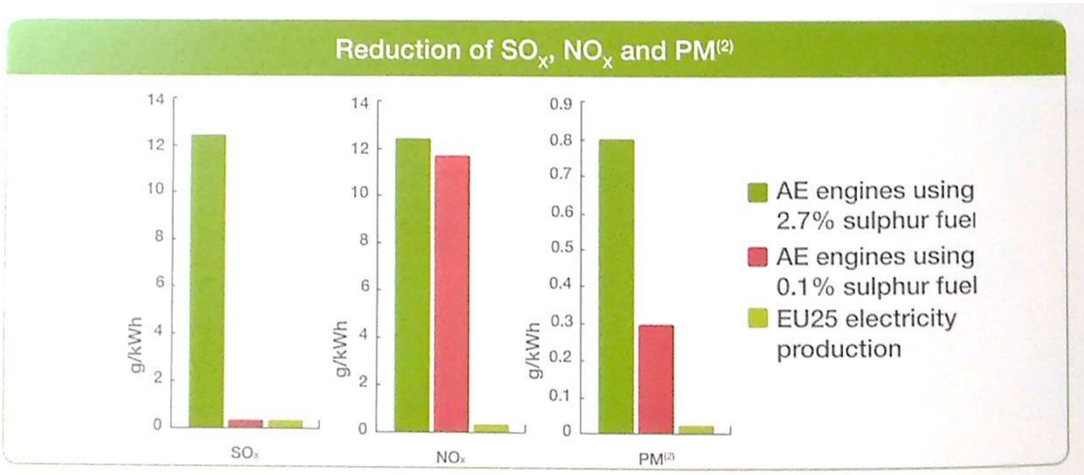

Figure 2: Comparison of emission reductions with different electricity sources [7]

The use of the Electrical Shore Connections could be useful to reduce the total emissions of a ship, which have already been estimated for the cruise Port of Barcelona **[3]**.

The second reason to use the HVSC is that is a way to reduce the harbor's noise. Ports have usually high levels of noise, and it may affect to the people's health producing diseases as hearing impairment, hypertension, sleep deprivation or many others **[8]**. The main cause of this noise is having ship's auxiliary diesel engines working to maintain all electrical devices (the noise can reach up to 120 dB near the engines). The high sound, and the vibrations attached, affects not only the crew and ship's passengers, but port's workers and even people living in the harbor's surroundings.

By using the Shore-side electricity, all the noise and its consequences are completely eliminated, because the engines creating it can be shut down.

The third reason mentioned is the possibility to allow the engines to undergo maintenance. If they were being used to provide the ship's electricity it would be impossible, but since it is connected to the shore supply system, different repairs and maintenance activities can be done in the engines when the ship is at dock, as they are completely off.

Also affecting the maintenance subject, there is the fact that the use of the HVSC is capable of reducing the maintenance costs. The maintenance cost of an engine is estimated at 1.6 €/h of use, so if it is shut down during all the hours that the ship spends at dock, it is possible to obtain a considerable save.

The fourth reason is that having shore power connections installed at the port makes it differentiate from other harbors, as one with more modern and efficient installations. Besides being able to sell electricity to the ships plugging in at berth and earn money, the HVSC will help to position the harbor in the market as a clean energy provider, so it may become a preference for ship's companies who are interested in reduce their own emissions.

Some of the most important ports in the world have electrical shore connections in their installations, at least in a part of them. For example, the Port of Los Angeles, USA's largest container port, was the first one to use the cold ironing for container ships in one terminal (in 2004), and has extended the system through more berths in the following years. In Sweden, the Gothenburg Port (the biggest one in the Nordic countries) has also HVSC, and moreover, it has two wind turbines generating electricity, so it is a reference in the use of green energies and pollution reduction. Other relevant ports, such as the Port of Long Beach in the USA or the Port of Antwerp in Belgium, have also facilities that allow the ships to use the Shore-side electricity.

The fifth and last reason mentioned is that the electrical shore connections offer the possibility to do an economic save. For example, with the already mentioned cut in engine's maintenance costs (the annual save per ship is estimated in 9,600 €[1]). Or taking into account that the energy provided by an external grid is far cheaper than the one generated by the consumption of marine diesel fuel (approximately 159 against 207 $/MWh). Also, the system installed on a ship has its reflection on indexes related to the environment and energetic efficiency, which can be used to obtain benefits.

As an example, there are ports that use the Environmental Ship Index (ESI) as a factor to calculate ship's port fees. The best qualified can obtain a reduction of up to 10% of the fees.

2.3. Shore to ship

It has been explained that the main use of the shore-side electricity is to provide energy from a shore supplier to a ship, so it can turn off the engines avoiding generating air pollution, among other benefits. But it is not a simple process, as the electricity coming from the supply system can be very different from the one the ship's network need.

The power able to be provided by the national grid or any other means should be constant, between certain parameters, but every ship has its own electricity needs. The voltage required may be different in every case, and even the frequency doesn't have to be the same. That is why the electrical side connection must be able to perform these voltage and frequency transformations obtaining electricity of good quality, fitting the existing regulations.

The design of the electrical circuit that must perform this conversion is one of the big issues of the entire system, since everything depends of its correct operation. In further chapters, this circuit will be designed and analyzed, and simulation of its behavior in different conditions are presented.

Also, it is important to notice that this connection is used to provide energy to the ship replacing the auxiliary engines, but it is not possible to switch on the engines while the ship's network is connected to the shore grid. Doing it may affect badly to the system, altering and causing problems in the own engine, the wiring and all the connected elements.

But even if this failure happens, the system itself is ready to minimize the damage. Between the transformations that the electrical circuit must carry out, there is a step where the electricity can be found in the way of direct current. This step, which allows interconnecting two asynchronous systems, is also useful to prevent disturbances that may appear in any of the sides, like the ones by the mentioned cause, to propagate to the other network.

[1] Based on an average consumption of 1.2MW x 2000h at dock, a cost of 4€/h and maintentance every 16,000h of work **[7]**

As the name itself suggests, the HVSC operate with high-voltage electricity. This means that the value of the voltage used is in the order of kV. Using high voltage against low voltage has its own benefits, as it has a lower percentage of electrical losses.

2.4. Platform to shore

Despite the fact that the primary use of the HVSC is supplying the elements of ships at berth, there is also other use that is going to be observed. The purpose is to go in the opposite direction: instead of using the shore grid to provide energy, it is going to be the one to receive it.

The causes why the earth grid could need an extra amount of power are diverse. As examples, it could be a natural disaster capable of interrupting the distribution, a failure of the generating plant, an unexpected situation that requires an increment of the energy needed… Whatever the cause is, the fact is that an external source of electricity would be necessary.

And this external source would be a floating platform, a supply ship or any other marine construction able to create its own electricity by independent means. Again, the source of this energy could be whatever: wind power, solar energy, hydropower… As an isolated platform in the middle of the sea, it is logical that the most common sources were renewable energies.

Although it is not the same situation that in the shore to ship case, the same problem does appear. The electricity created by the platform’s system would have a different voltage and frequency from the national’s grid, so a circuit to transform these values and make possible the connection between the two systems would be needed again.

3. Grid characteristics: voltage and frequency

The values of voltages and frequencies of the electrical grid are not constant all over the world. These values are different depending on the country, as it is shown in Figure 3:

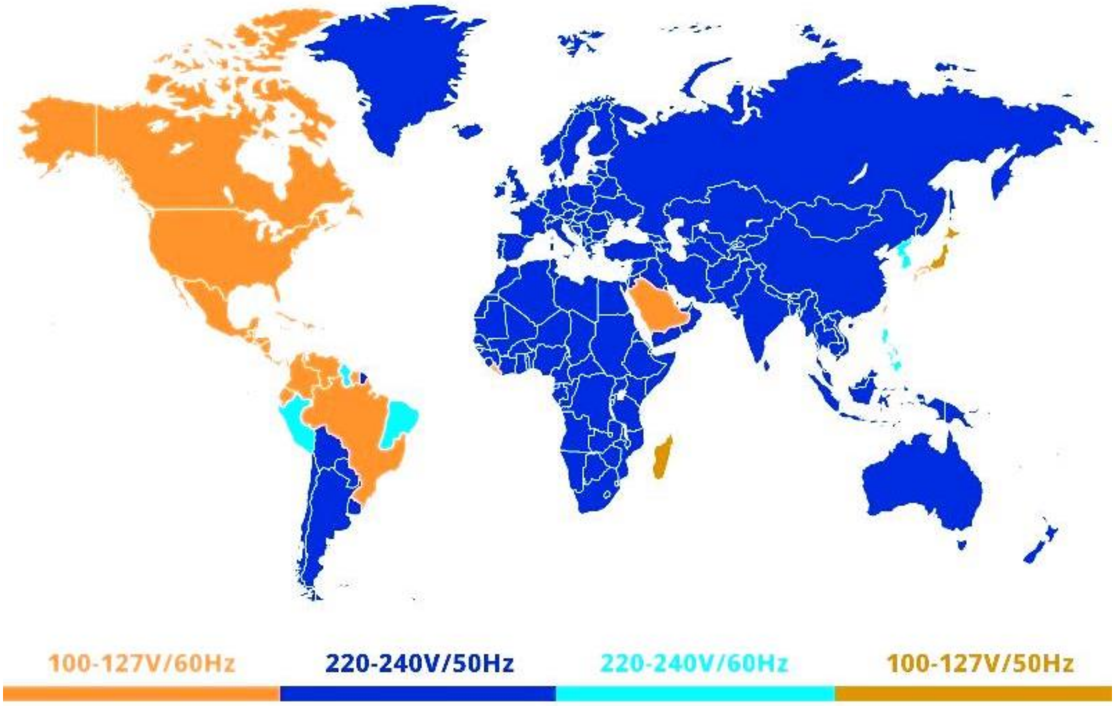

Figure 3: Values of voltages and frequencies [11]

As the figure shows, there are two ranges of voltage in which the network operates, as well as two values for the frequency. The voltage provided by the system in plugs oscillates between 100-127 V or 220-240 V, while the frequency of the alternate current may be only of 50 Hz or 60 Hz.

The determination of the frequency values is due to historical reasons. In the two big zones of influence in the development of electrical systems, Europe and the USA, the engineers of the main electrical companies of the zones, Allgemeine Elektrizitats Gesellschaft (AEG) and General Electric (GE) respectively, had to solve different issues from the late 19th century. As each company had its own problems and ways to solve them, each one arrived to solutions with the frequency that best fitted. As each company was the most influent in its zone, the rest finally adopted the same work frequency, leading in the following years to a world divided by the electricity's frequency **[12]**.

So there are two frequencies, as well as two ranges of voltage, and obviously everything built in a certain country is usually created to work with the electricity's frequency and voltage of the place where it has been built or manufactured. This includes the ships, besides all port's electrical installations.

The problems with ships appear when they travel around the world and have to berth at a pier with different electricity's frequency from the ship's own and have to use the shore power connections. In this case, it is vital to do a conversion of the frequency from the national's grid to the one of the ship's network, besides changing also the voltage of the power supplied. This conversion must be done by the HVSC circuit.

3.1. National grid

To talk about the characteristics of the Spanish electrical national grid, the basic fact to be remembered is that it is included in the group of 220-240 V (providing an approximate value of 230 V at common plugs) and 50 Hz, like all Europe. Besides that, there are a lot of other data that must be considered.

The *Red Eléctrica de España* (Electrical Grid of Spain) is the corporation operating the national electricity grid in Spain, being in charge of the transmission system of power since 1985. At present, the transmission grid has about 40,100 lines of high voltage and a length of over 40,000 kilometers, taking into account the grid of the peninsula and both the Balearic and Canary Islands. At the same time, all the circuit can be divided between the wiring that transmits electricity at 400 kV and the one that does it under 220 kV, as it is seen in the following table:

Year 2016	Peninsula grid	Balearic Islands grid	Canary Islands grid	Total grid
Km of grid at 400 kV	21,181	432	216	21,829
Km of grid at ≤220 kV	18,949	1,368	1,131	21,448
Total Km	40,130	1,800	1,347	43,277

Table 1: Km of electrical grid in Spain [15]

The national installed power of the whole grid has experienced a significant increase compared to the one existing ten years ago, although in the last five years this power has remained quite steady:

Year	2006	2007	2008	2009	2010	2011
National installed power (MW)	81,515	88,115	94,197	97,801	101,420	102,960

Table 2: Installed power in Spain from year 2006 to year 2011 [16]

Year	2012	2013	2014	2015	2016
National installed power (MW)	105,325	105,887	105,792	106,187	105,372

Table 3: Installed power in Spain from year 2012 to year 2016 [16]

It is also possible to obtain information about the sources that generate this energy. For the year 2016, the distribution of the origin of the national installed power is the following:

Source	National installed power (MW)
Hydraulic (conventional and mixed)	17,055
Pumping	3,301
Hydraulic	20,356
Nuclear	7,573
Coal	10,056
Fuel + gas	2,490
Combined cycle (including open cycle)	26,670
Hydro Eolic	11
Eolic	23,020
Photovoltaic solar	4,667
Thermic solar	2,300
Renewable thermic, biogas, biomass, marine hydraulic and geothermic	747
No renewable thermic and cogeneration	6,728
Waste	754
Total	**105,372**

Table 4: Sources of power in Spain in 2016 [16]

The source with the highest installed power is the combined cycle, as it is responsible of more than a 25% of the total. Besides this, other processes that claim to be a huge origin of the national power are the Eolic, the hydraulic and the conventional and mixed hydraulic. Only these four sources provide up to the 82% of the entire installed power, being the Eolic power the leading one in terms of renewable energy sources. It has to be clarified that installed power is not the same that the produced electrical energy of the grid, as it depends of various conditions affecting the source such as: availability, wind force (in case of Eolic sources), water level of the reservoirs (in hydraulic sources)… These conditions will affect the power production, leading to the generation of electrical energy that can be observed in Table 5:

Source	National electrical balance (GWh)
Hydraulic	30,819
Nuclear	54,755
Coal	52,789
Fuel + gas	6,497
Combined cycle	29,357
Hydro Eolic	9
Eolic	48,109
Photovoltaic solar	8,236
Thermic solar	5,085
Renewable thermic, biogas, biomass, marine hydraulic and geothermic	4,625
Cogeneration	25,108
Waste	2,196
Total	**267,584**

Table 5: Electrical balance in Spain in year 2015 [17]

Here it can be seen that although nuclear and coal sources have a relatively small installed power, each of them account around a 20% of the total generated electrical power. With almost an 18%, the Eolic is the third most important source, while hydraulic, the combined cycle and cogeneration are responsible each one of approximately a 9 – 12% of the produced electricity.

It must be remembered also that even though the electrical grid is elevated to high voltage (220-400 kV) before starting with the distribution of the energy, it does not have this voltage in the entire transportation system. The transmission of power at high voltage has fewer losses, but in certain points of the system the voltage must be reduced. This happens in installations called substations, where transformers decrease the high voltage to what is called medium voltage (between 1-36 kV). There is not a determined value for the medium voltage grid, as it might change depending of the zone, but the most common values are 13.2 kV, 15 kV, 20 kV and 30 kV. After traveling with the medium voltage, the electricity reaches the transformation centers, where again a transformer is able to reduce the power to low voltage, to approximately 230 V, which is the voltage value that reaches plugs in houses, businesses and small industries.

3.2. Ships

On the ship's side happens approximately the same that on the land. The selection of the frequency is simpler, as it can take only the value of 50 Hz or 60 Hz. The election of this value, as has been already explained, depends on where the ships and the electrical systems are built.

But regarding the voltage, a wide range of voltages is used between all the elements connected to the electrical network, resulting in a very diverse number of voltages. As an example, this table of the Society of Classification Bureau Veritas shows the maximum voltage allowed for various ship services:

Use		Maximum voltage V
For permanently installed and connected to fixed wiring	Power equipment	1000
	Heating equipment (except in accommodation spaces)	500
	Cooking equipment	500
	Lighting	250
	Space heaters in accommodation spaces	250
	Control (1), communication (including signal lamps) and instrumentation equipment	250
For permanently installed and connected by flexible cable	Power and heating equipment, where such connection is necessary because of the application (e.g. for moveable cranes or other hoisting gear)	1000
For socket-outlets supplying	Portable appliances which are not hand-held during operation (e.g. refrigerated containers) by flexible cables	1000
	Portable appliances and other consumers by flexible cables	250
	Equipment requiring extra precaution against electric shock where a isolating transformer is used to supply one appliance (2)	250
	Equipment requiring extra precaution against electric shock with or without a safety transformer (2)	50

(1) For control equipment which is part of a power and heating installation (e.g. pressure or temperature switches for start/stop motors), the same maximum voltage as allowed for the power and heating equipment may be used provided that all components are constructed for such voltage. However, the control voltage to external equipment is not to exceed 500 V.
(2) Both conductors in such systems are to be insulated from earth.

Figure 4: Maximum voltage allowed for different services (BV) [39]

And as it can be seen, the maximum voltage allowed for different elements change in such a big range as from 50 to 1,000 V.

Besides this low voltage consumers, in ships also exist systems distributing energy at medium and high voltage. The circuits of medium voltage usually operate between 3.3 V and 6 kV, while the high voltage systems work with much higher values. Anyway, looking at it from the installation point of view, the Rules of Societies of Classification forbid to install in the same enclosure low voltage systems and systems with voltages above 1 kV, in order to avoid problems and safety issues.

When speaking of the power that can be given to the ship's network through the HVSC, it is possible to talk in values of the order of MVA. The following image gives an idea of the approximate power required by three different kinds of ships, power that must be provided by the on-shore supply system:

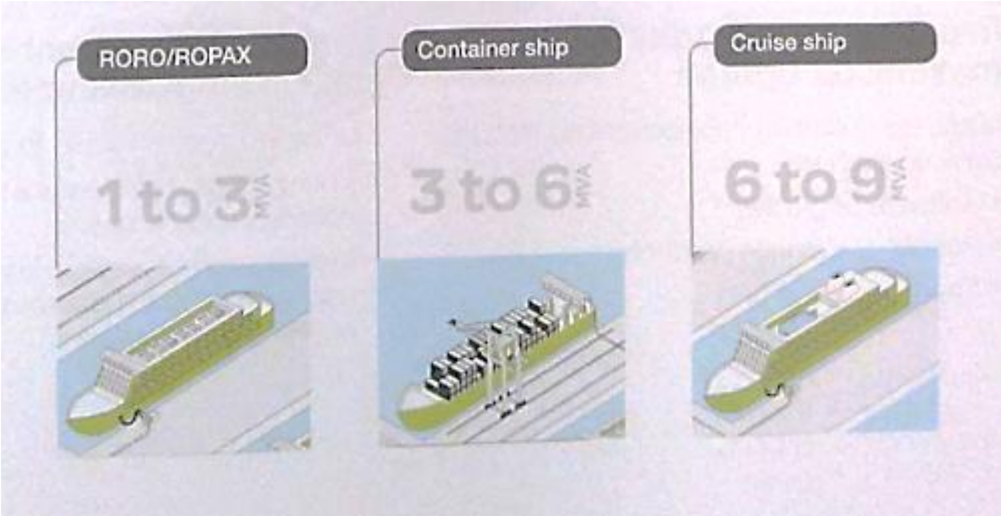

Figure 5: Average power of different ships [7]

Moreover, it can be taken into account the fact that the total volume of installed power in a ship is really huge, and it is getting even bigger with the construction of every time longer ships, like the most modern container ships. For example, one of these big container ships may have a total installed power of up to 80-100 MVA, which is a considerably large amount of energy **[20]**.

4. Characteristics of the main components

The circuit of a High-Voltage Shore Connection is formed by many different components interacting with each other, in order to finally obtain the power with the desired voltage and frequency. In this section, the main elements forming the system will be shown and explained.

The general idea of what the circuit must do is simple. There is a source of energy with alternate power, providing a certain voltage with a determined frequency, and these voltage and frequency have to be transformed to fit with the requirements of the ship's electrical network. To do this change, the circuit must have the following basic structure:

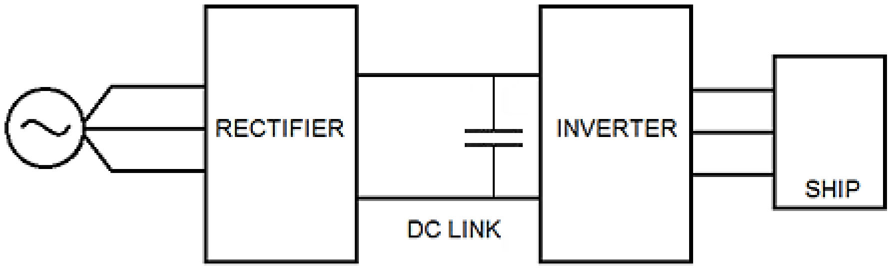

Figure 6: Basic design of the system

The energy provided must reach the rectifier, where it is going to be transformed from alternate to direct current. After going through the electrical feeder in DC, it will arrive at the inverter, where it will be turned into three-phase AC again, but with the specifications that the ship requires.

More details will be given in the upcoming sections.

4.1. Source

The source of power is the one that supplies the entire circuit. It is designed to provide electricity with determined values for parameters as the kind of current, the amplitude, the phase or the frequency, and even if it is a single-phase or a three-phase source.

The case of this project is a three-phase system, so a three-phase voltage source will be needed. Also, it must be remembered that the source of this circuit is representing an input of energy from the electrical national grid or any other power generating element, so the parameters of the source must be coherent with the real origin of the electricity that will supply the HVSC system.

The real source of power of this project would be the electrical national grid, whose details and characteristics have already been explained. So, there are some features of the implemented source that must correspond with the ones from the national grid.

Basically, the source must be an AC and a three-phase system. While the amplitude of the source may be adapted to the needs, one fixed parameter is the frequency: like in the Spanish national grid, it must be 50 Hz. If the ship that is going to connect itself to the shore-side electricity operates with another frequency, then this frequency conversion will have to be one of the steps that the system of the HVSC must do.

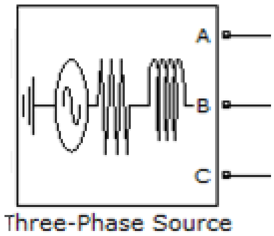

Figure 7: Power source

4.2. Transformer

The transformer is the element in charge of changing the voltage (increasing or decreasing it) of an AC electrical circuit, while keeping the power of the input. It works based on the principle of the electromagnetic induction, whereby a voltage is originated in a body exposed to a variable magnetic field, creating an induced current when the body is conductive.

Basically, a transformer consists of:

- A magnetic core, formed by ferromagnetic metallic sheets, with the mission of maintaining the magnetic flow inside of it in order to avoid the electrical losses.
- An input or primary winding, formed by a copper wire surrounding a leg of the core. The bigger the number of turns in the winding, the higher the induced voltage will be.
- One or two outputs (or secondary windings) also formed by copper wires surrounding each one a leg of the core, with a determined number of turns.

There are also other elements such as safety relays, control panels and devices designed to change the relation of transformation of the transformer.

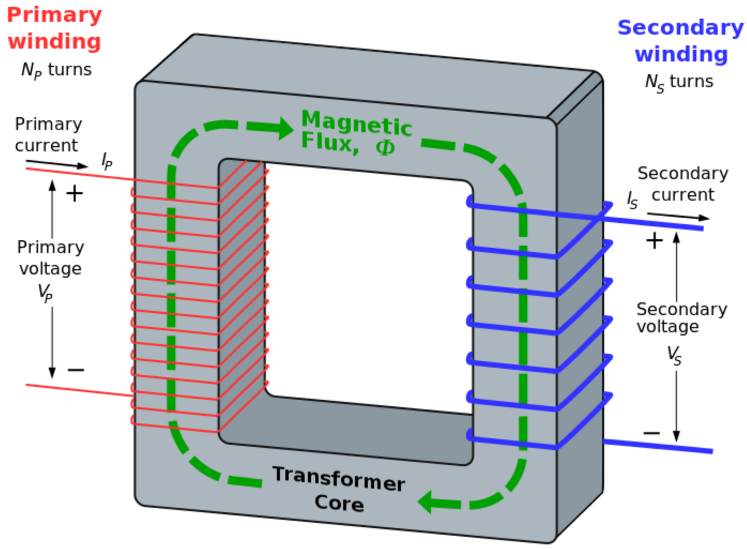

Figure 8: Transformer [23]

Transformers may be three-phased, and so they are able to provide a larger power in a more efficient way. In this case they have three windings in the primary leg, as well as three windings in the secondary leg. For each one of the windings exist two configuration options: the star (Y), which may have an accessible neutral, or the delta/triangle (Δ) configuration.

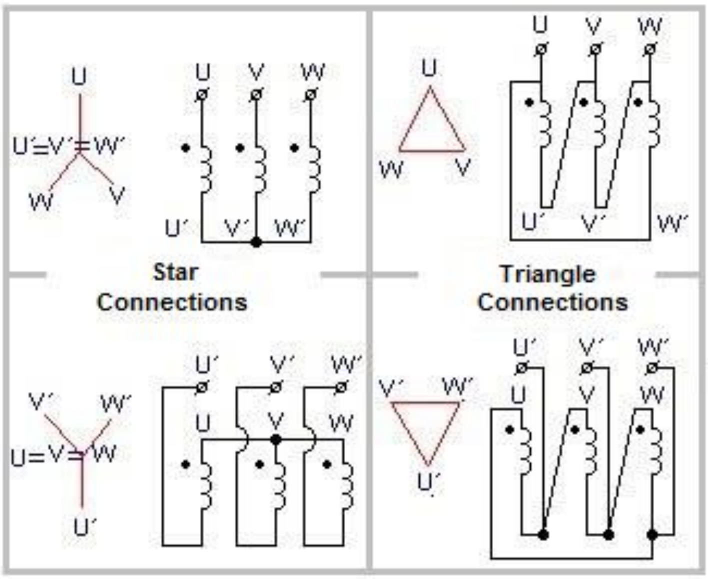

Figure 9: Star and triangle connections [24]

When there are two secondary windings in a transformer, it is called a three-phase transformer of three windings. This kind of transformers is found usually in electrical systems, especially in the interface between the transmission and the distribution grid. At least one of the output windings must have the delta configuration mentioned above, in order to eliminate problems such as the apparition of harmonics.

The three-phase transformers of three windings are widely used nowadays, and one of them is going to be implemented in the circuit of the HVSC to regulate the energy received from the source of the national grid and to adapt it to the needs of the berthed ships. However, there are other applications for these transformers. For example, they are commonly used in rectifying systems for regulating the speed of marine engines. These electronic speed regulators are every time more present in big engines, at the expense of reducing the utilization of mechanical regulators. The main reason for this progressive substitution is the fact that electronical regulators are more precise than the mechanical ones (the electronical only allow a variation of the speed of approximately 0.25%, while the mechanicals can reach a variation of up to 5%). As these marine engines must operate at a constant number of rpm, an accurate speed regulation is truly important.

4.3. Rectifier

The rectifier is the component that converts energy in AC to DC. There are different kinds of rectifiers:

- Non-controlled: they are formed by diodes, so they do not need any external sign to conduct or stop conducting electricity.
- Controlled: instead of diodes, the rectifier is formed by thyristors or transistors, which are monitored through a control circuit. This allows having a variable voltage at the output.

In this case, only non-controlled rectifiers are going to be considered, as they are the ones that are going to be implemented. At the same time, rectifiers can be either single-phase or three-phase, depending on the power source. This project is designed to work with a three phase system, so these are going to be explained.

Working with three-phase AC in a rectifier allows obtaining a pretty regular voltage output, even without using a filter. The reason is that this voltage never reaches zero, as the three phases combine themselves to increase while others decrease. The combination of the phases is done thanks to the use of bridges of diodes. The number of diodes used in a rectifier may vary, although is always a multiple of three.

The differences of using more or less diodes can be seen in the continuity of the resulting voltage. Two examples will be given next to in order to compare their results.

First, there is this rectifier formed by six diodes, three of them joined by the cathodes to the positive output, and the other three joined by the anodes to the negative output. The capacitor is not taken into account, as the discontinue line indicates that it must be connected when using the rectifier joined with other converters:

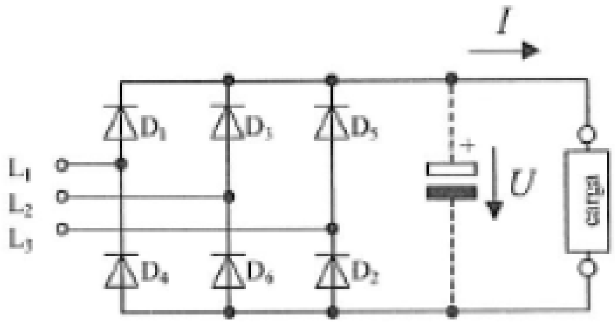

Figure 10: Rectifier of six diodes [35]

The resulting voltage must have waves, where will be found six pulses in every cycle. If the frequency has a value of 50 Hz, then the duration of each cycle is of 0.02 seconds. Observing the following image, it is seen that the pulse is repeating itself six times between 0.15 and 0.35:

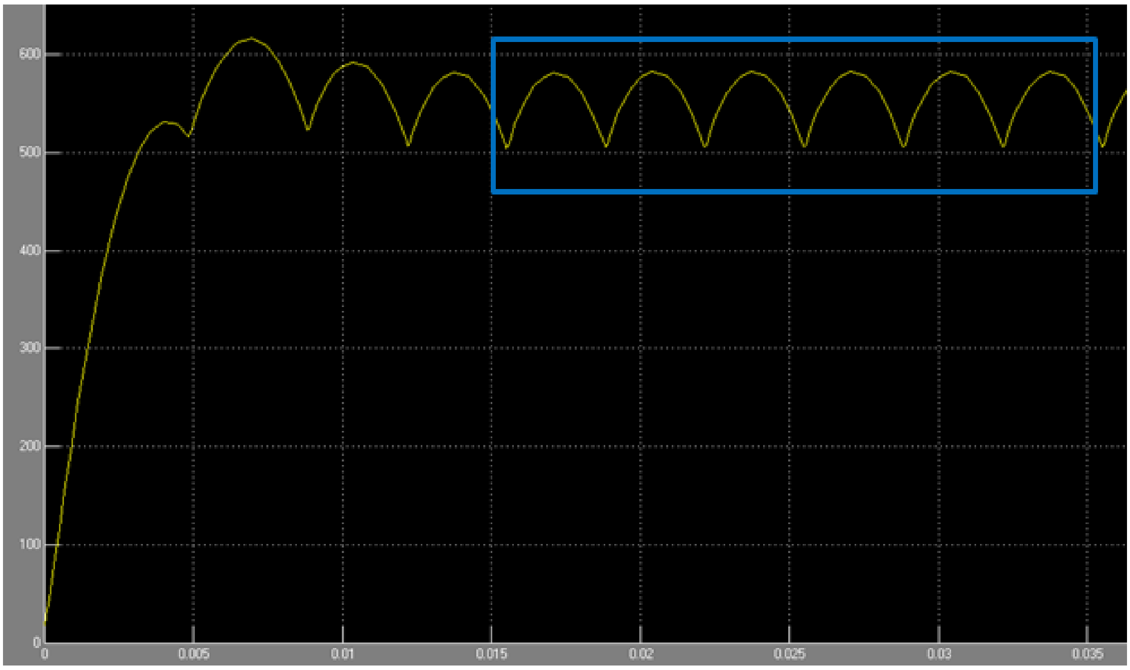

Figure 11: Voltage after a rectifier of six diodes

The second example is a rectifier with twelve diodes organized around the two windings of a transformer. In this case, there are also three joined by the cathodes to the positive output, and other three joined by the anodes to the negative output, but there are six more diodes in the middle connecting it all:

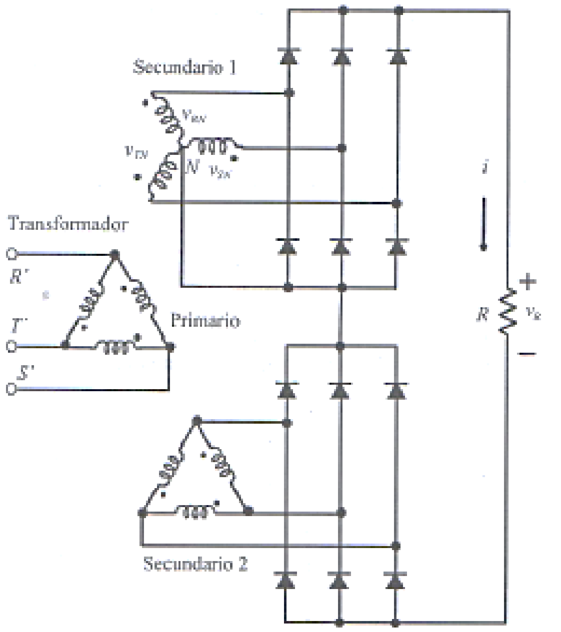

Figure 12: Rectifier of twelve diodes [35]

The resulting voltage will have pulses too. As the first example had six diodes and six pulses in every cycle, this circuit will have the same relation. Remembering that the input frequency is of 50 Hz, twelve pulses will be found in a cycle of 0.02 seconds, as it can be seen between 0.15 and 0.35:

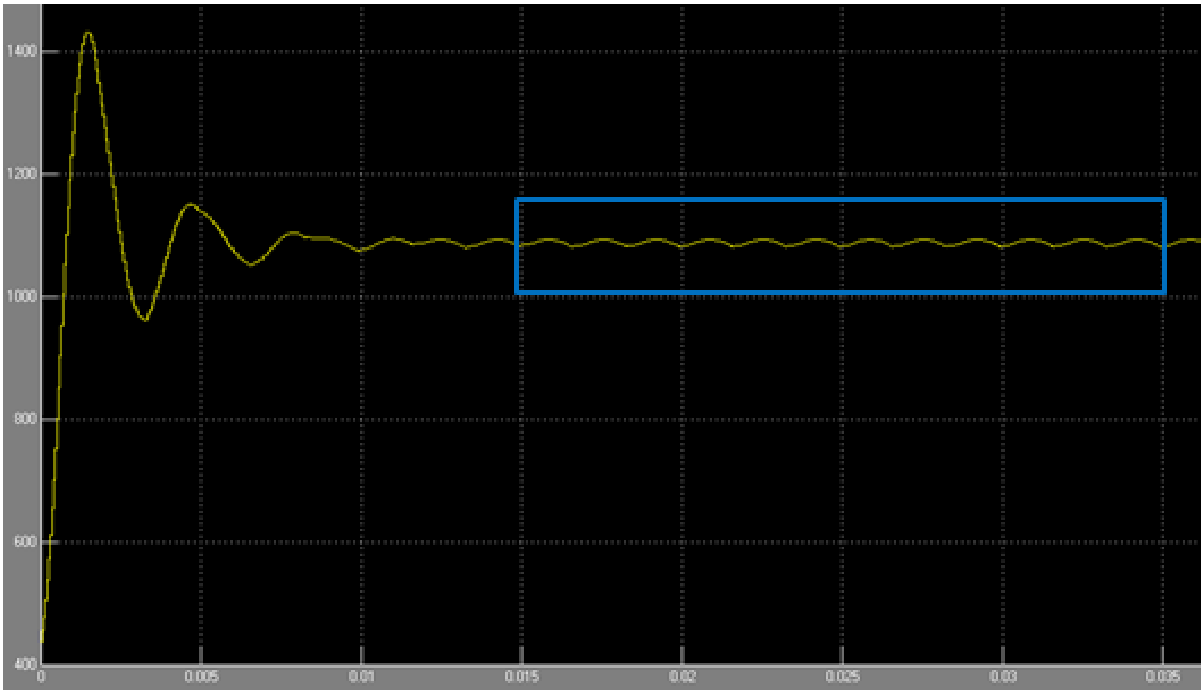

Figure 13: Voltage after a rectifier of twelve diodes

From this comparison, it can be deduced that a rectifier with twelve diodes will produce a softer DC with less variations, so one of this kind will be used in the design of the HVSC circuit.

4.4. Universal bridge of diodes

The universal bridge is an element that implements a set of power electronic devices, instead of using individual switches. The devices implemented can be diodes, thyristors, GTO, MOSFET, IGBT, ideal switches…

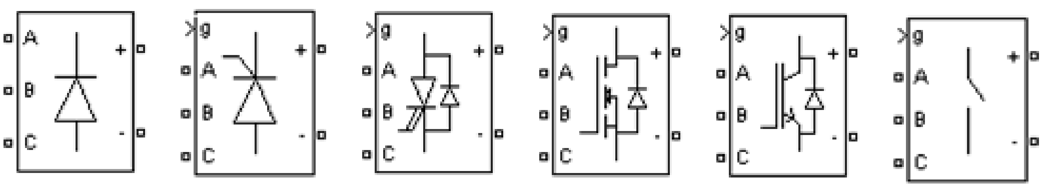

Figure 14: Possible configurations of universal bridges [30]

This element is formed by a bridge of up to six power switches connected in a bridge configuration, where the number of arms can be selected. The universal bridge is the basic block to build a rectifier like the explained previously, as it is used to transform the three-phase AC into a DC.

For this project, universal bridges with three arms and six diodes will be implemented. The internal disposition of the block is like in the following figure, where the number of each diode indicates the order of commutation:

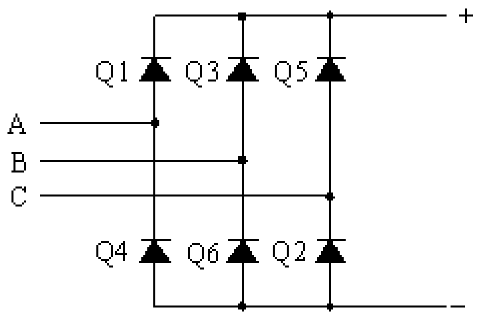

Figure 15: Order of commutation of the diodes in the universal bridge [30]

The diodes forming this universal bridge belong to the family of power semiconductors, whose name is due to the fact that they only conduct energy in some circumstances. In the case of the diodes, they are formed by two terminals: the cathode and the anode. Its operation consists of simply conducting energy from the anode to the cathode, while ideally it does not allow the current go through from the cathode to the anode.

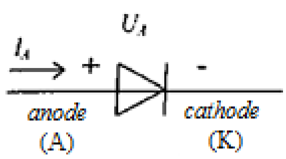

Figure 16: Diode [33]

This way, a universal bridge of diodes is a basic element to rectify the current and make the HVSC work.

4.5. Inverter

The mission of an inverter is to transform energy in DC to AC. The inverters can be also single-phase or three-phase, just like the rectifiers. As it has been already said, this project is using a three-phase system, but single-phase inverters will be explained first. In fact, it is easy to obtain a three-phase inverter from a single-phased one.

The design of inverters is based on bridges of interrupters that are opened and closed alternatively to obtain at least two different values of voltage from a DC, which has a single voltage value. The resulting voltage values create the corresponding pulses of the AC. As it is creating a waving output from a straight line, it must be remembered that the frequency of the resulting current has to be specified, because it is not information that can be extracted from the DC. This frequency must be selected, and taken into account to be able to control the results.

The way to control the shape of the AC in the output is through the control of the interrupters. There are different options to monitor the interrupters, but they are all based in the emission of pulses. These pulses are generated generally by an external source, and they can only take two values: zero or a natural number (usually, number one). The system of the pulses is activated with the desired frequency for the AC, and so the resultant wave will have this frequency.

Now some examples of inverters will be shown, in order to identify the main differences and compare them.

The first example is a single-phase inverter of two levels, using four interrupters in each one, controlled by pulses in form of quadratic waves. Here, each one of the DC voltage sources has the voltage value of one of the levels of the resulting wave, and it is manually indicated in the pulse generators when they must release a high or low signal, and during how much time of the entire wave period.

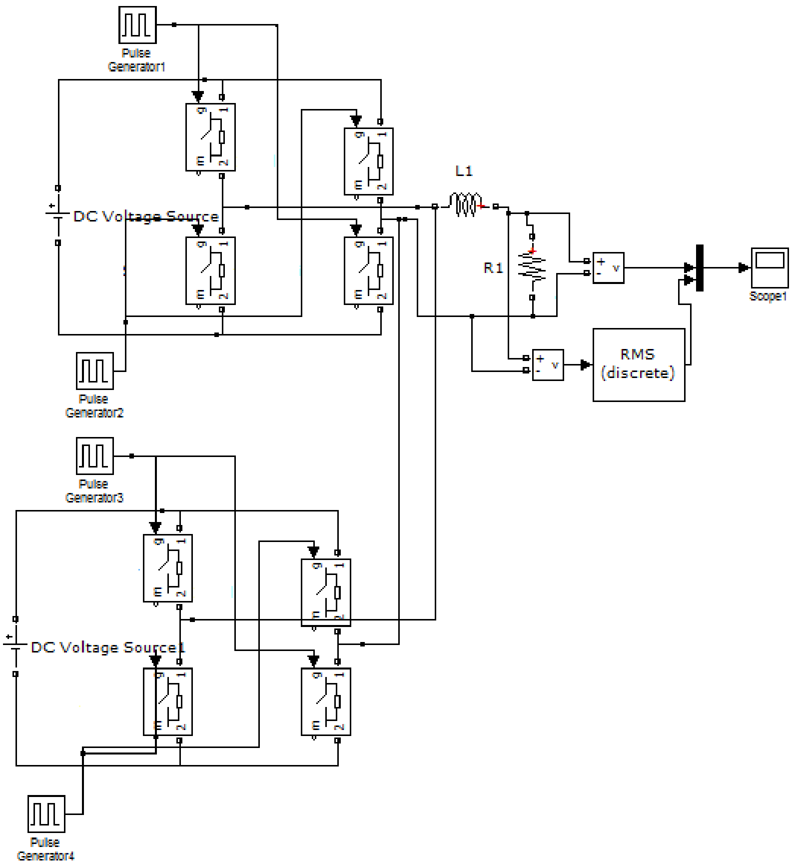

Figure 17: Inverter of two levels

The resulting wave of this inverter is the following figure, where the two different voltage levels can be observed, as well as the RMS voltage:

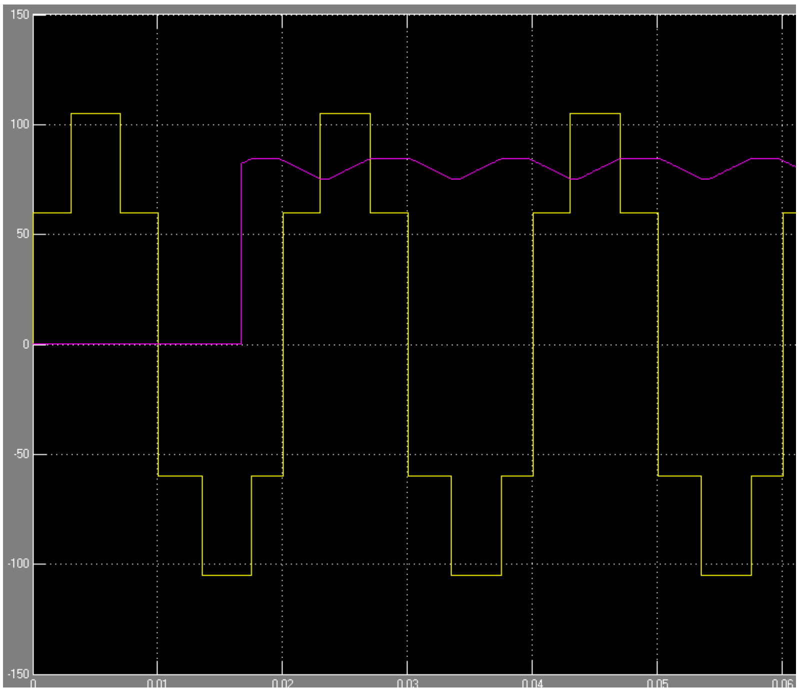

Figure 18: Voltage after inverter of two levels

This two-level inverter can be converted into a three-level one by just adding another bridge of interrupters (having a total number of twelve interrupters), with its respective DC source and pulse generators. After readjusting the timing of the pulses, an AC wave like the following can be obtained, with a more accurate sinusoidal shape:

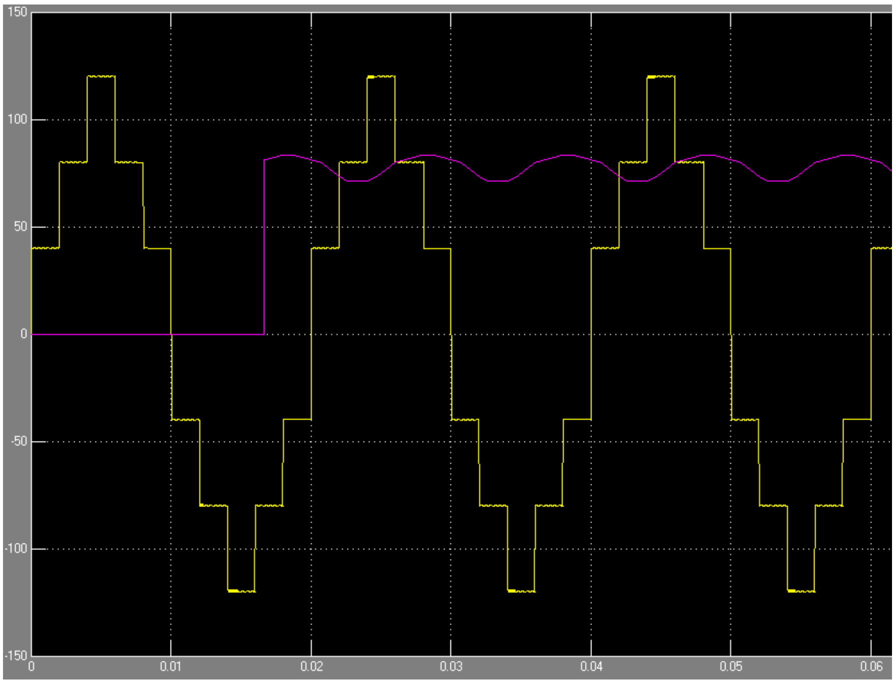

Figure 19: Voltage after inverter of three levels

From this last example, transforming it into a three-phase system is as easy as replicating the design twice and timing accurately the three phases. For this step, it must be remembered that the phases have a delay of 120º between themselves, and it has to be introduced in the generation of the pulses. The resulting AC signal is the following:

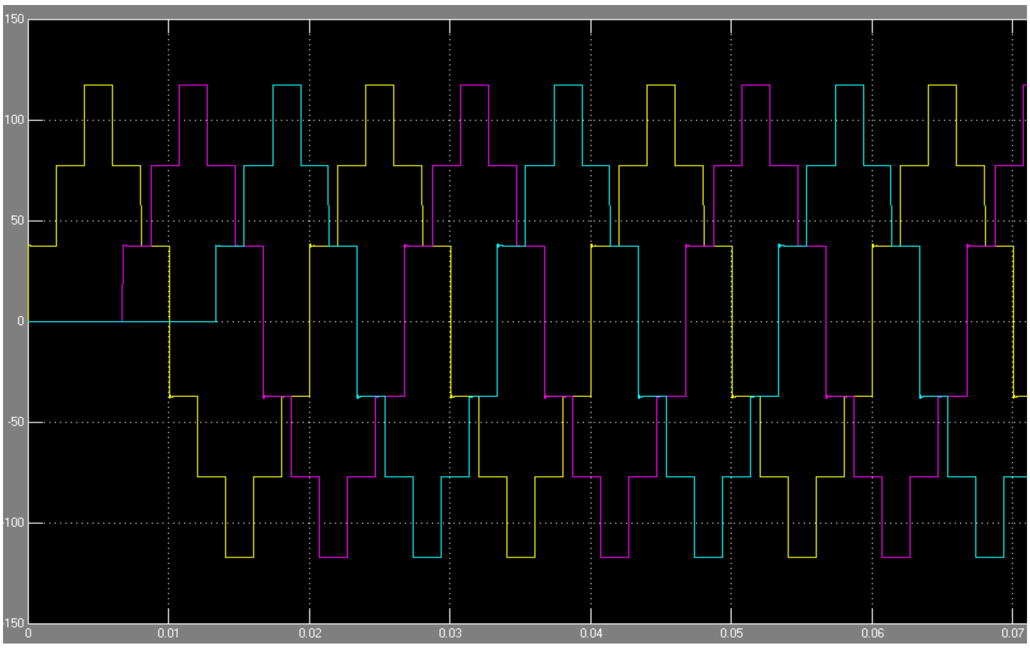

Figure 20: Voltage after a three-phase inverter of three levels

Another way to implement an inverter goes through using the same DC voltage source for all levels, besides controlling the interrupters with Pulse-width Modulation (PWM) instead of independent pulses. An example of a three-phase inverter of this kind is the following figure:

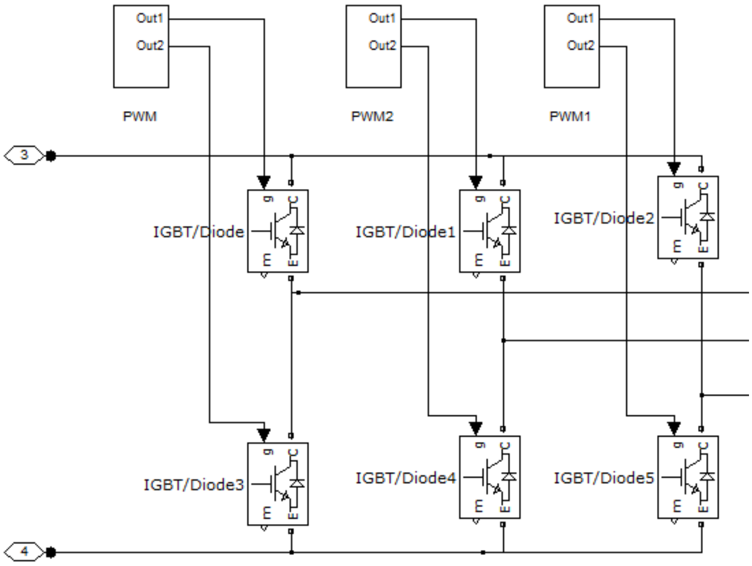

Figure 21: Three-phase inverter controlled by PWM

Thanks to the use of a set of inductances, one in each electric feeder, after this configuration of the interrupters and this way of controlling them (which will be explained in its respective section), it is possible to obtain a three-phase wave like the following one:

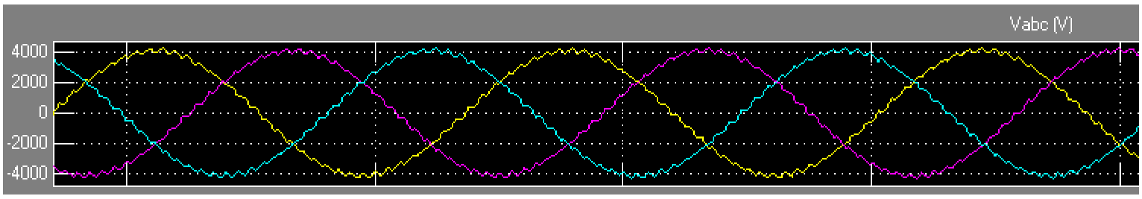

Figure 22: Voltage results after inverter controlled by PWM

As it can be seen on these examples, the use of the PWM gives a far more accurate result than any that could be obtained through the pulse generation. Besides, the last example also shows how to produce a three-phase AC wave from one single input of DC, just like the input that will have the inverter in this project. Moreover, it must be noticed that this example is not using regular interrupters, but IGBT/Diodes, which offer some advantages compared to normal interrupters. Due to all these reasons, an inverter like the one appearing in the last example will be implemented in the system of the project.

4.6. IGBT/Diode

An IGBT/Diode is an element which has an IGBT and a diode installed in antiparallel. While the diode of this block is like the one explained previously in the universal bridge section, the IGBT is also from the family of semiconductor devices. What differences an IGBT is that it is an interrupter controllable through an external signal, which indicates when the IGBT must be closed or opened.

The IGBT (Insulated Gate Bipolar Transistor) is divided in three parts. There are the collector, the emitter and the gate:

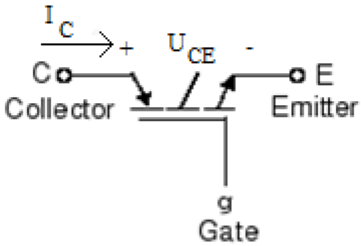

Figure 23: IGBT [30]

The IGBT turns on when the voltage between the collector and the emitter is positive and a signal with a value above zero is applied at the gate input. It turns off when this voltage is still positive but the input signal is zero, and it turns into the off state when the collector-emitter voltage is negative. When the IGBT is in this off state is when it does not conduct, so the current goes through the antiparallel diode.

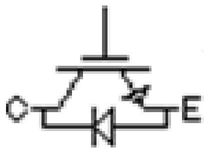

Figure 24: IGBT/Diode [30]

The possibility of the IGBT/Diode to conduct between two voltages when the signal indicates it is what makes this element the basic component for the design of the inverter of this project.

4.7. PWM

One of the most used techniques to control the commutation of converters and externally regulated elements is the Pulse-Width Modulation (PWM). This technique consists basically of comparing a triangular wave of a very high frequency with a sine wave: depending of the relative position of the two waves, one signal or another will be released, and so the interrupter will be opened or closed.

The triangular wave is called the carrier signal, and it has a frequency in the order of kHz; in fact, the frequency for the carrier signal that will be considered for this project is of 10 kHz. On the other side, the sine wave is the modulating signal, and its frequency is of 50/60 Hz in cases like this, when it is desired to commutate the interrupters to generate AC signals and they must turn on and off appropriately for the selected frequency.

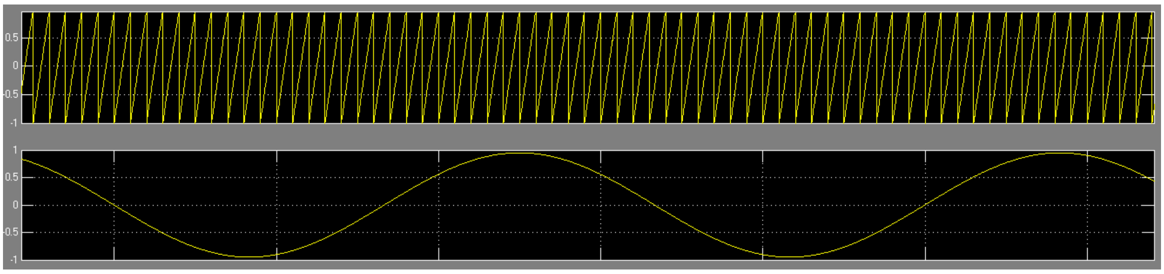

Figure 25: Waves generated for the PWM

So when the carrier signal (triangular signal) is greater than the modulating one (sine signal), the resulting value of the comparison is 0 and the interrupter is closed. But when it is the sine signal the one that is greater, then the output value of the comparison is 1, and the commuting elements switches on.

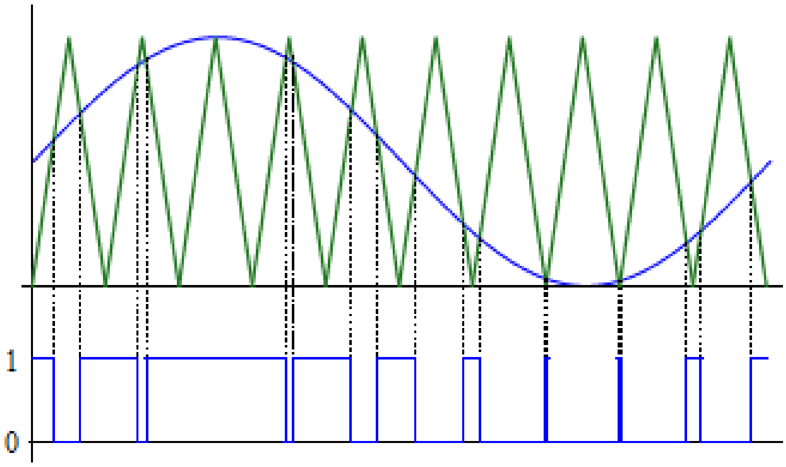

Figure 26: Comparison of waves in PWM [26]

The resulting signal will be a modulated wave that only takes two values, 0 or 1, where the time that this value remains the same depends on the relative position of the carrier and the modulating waves. So, the pulse with a value of 1 will last longer when the amplitude of the sine wave is near its highest point, while this same pulse will be very brief when the mentioned amplitude is around its lowest point.

Once one PWM signal is adjusted, it must be remembered that each half-bridge of a converter, like in the case of the inverter that is being designed in this project, consists of two interrupters (or two IGBT, to be more precise). This two IGBT can't receive the same PWM signal; otherwise, they would turn on at the same time, causing short circuit and damaging all the electrical elements. That is why to activate the second IGBT a second PWM signal must be generated. This signal will have to be the opposite of the previous PWM signal, so they never coincide emitting a signal of value 1.

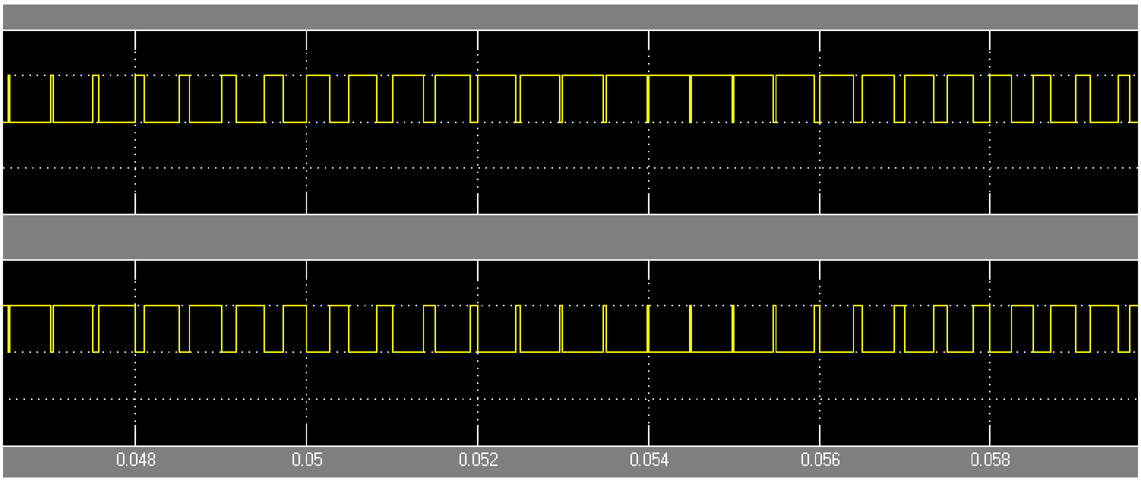

Figure 27: Signals generated by the PWM

This two waves will be able to activate two controllate interrupters, which will generate a single-phase electric feeder of AC. But if a three-phase system is wanted, as in the objective of this project, then two more generating PWM signals systems will have to be added, as well as the necessary elements to create its respective opposite signals. In total, there will be six different PWM signals, and each two will generate a single-phase AC output. In order to make a right three-phase AC system, the difference of phases between the system of pulses activating each half-bridge must be taken into account: it is a gap of 120º between each phase, which must be introduced in the origin of the sine waves.

5. Applicable rules

Although Classification Societies have stablished a huge deposit of rules and standards applicable to all possible elements and systems of ships, it is a fact that there is almost no information regarding the HVSC in most of them.

For example, Bureau Veritas only has some general requirements of shore-side electricity inside the chapters of general electrical rules. Other Classification Societies, such as Lloyd's Register or the American Bureau of Shipping, have some concrete rules about the topic, but only referring to the ship side of the installation. Meanwhile, Classification Societies as the DNV and RINA have rules and regulations related with the shore connections that affect both sides, the ship and the pier, with different levels of detail.

As the Classification Societies do not offer so many regulations about the HVSC on the shore side, which is the topic of this project, other rules must be searched. So here it is found the International Standard IEC/ISO/IEEE 80005-1: "Utility connections in port – Part 1: High Voltage Shore Connection (HVSC) Systems – General requirements", which stablishes the international requirements that these installations must fulfill in any port.

5.1. The International Standard 80005-1

The standard IEC/ISO/IEEE 80005-1 has been drafted between three institutions: the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO) and the Institute of Electrical and Electronics Engineers (IEEE). These are organizations with worldwide presence, whose objective is to develop standards that can be applied anywhere, each one in its own scope. In the particular case of this standard 80005-1, it covers a subject where the three have influence, so they have teamed up to develop the document.

The main objective of this standard is to define the requirements that support the efficiency and safety of connections between ships and high-voltage shore power supplies, through a compatible connection and following the appropriate procedures. So the compliance of all the requirements of the standard on the shore side would allow different ships to connect to the HVSC in piers from all over the world without problems or misunderstandings.

This section of the project will be focused on identifying the requirements that this standard sets for the parameters of the power transmitted by the HVSC, as well as on the safety conditions of the shore side of the system.

5.1.1. General requirements

Between the general requirements stablished by the standard, there are different groups in which the requirements may be divided. These groups are the ones that appear below.

5.1.1.1. Protection and safety systems

- Effective means must be provided to prevent an increase of moisture and condensation in the equipment is, including when it is not going to work during appreciable periods.
- HVSC equipment shall be installed in access controlled spaces, and it shall be suitable for the environment conditions in the space where it is expected to operate, complying with the applicable requirements of the corresponding standards (IEC 60092-101 and IEC 60092-503).
- HVSC equipment shall be located outside the hazardous areas (where flammable gas, vapor or combustible dust may be present) of the shore facilities under normal operating conditions, except where it is shown to be necessarily located in these areas for safety reasons.

5.1.1.2. Electrical requirements

- Routine tests shall be performed for all HVSC system components according to the periodicity of the applicable standards.
- The high voltage shore supply and link nominal voltage is standardized at 6.6 kV or 11 kV AC, so any equipment of a ship requiring conversion to nominal voltage shall be installed on board.
- The prospective short-circuit contribution level from the high voltage shore side system shall be limited to 16 kA rms, unless further specifications.
- All the electrical system must be suitable for the prospective maximum short-circuit fault current. Equipment shall be rated for minimum of 16 kA rms for 1 second, and a 40 kA peak.

5.1.1.3. Emergency shutdown

- Emergency shutdown facilities shall be provided. When activated, they will instantaneously open shore connection circuit-breakers on shore and on board. Fail-safe, hard-wired circuits shall be used for this system.

- The relay contacts of the safety circuit shall be designed according to IEC 60947-5-1 and for a rated insulation voltage of U_1= 300 V, AC of 5 A, and DC of 1 A.
- In case of emergency shutdown, the high-voltage power connections shall either:
  - Be automatically earthed so that they are safe to touch;
  - Be arranged for manual earthing and routed and located such that personnel are prevented from access to live connection cables and live connection points by barriers or an adequate distance in normal operational conditions.
- The emergency shutdown facilities shall be activated in the event of:
  - Loss of equipotential bonding, via the equipotential bond monitoring relays;
  - Over tension on the flexible cable connecting shore and ship by mechanical stress;
  - Loss of any safety circuit;
  - Activation of any manual emergency-stop;
  - Activation of protection relays provided to detect faults on the HV connection cable or connectors;
  - Disengaging of power plugs from socket-outlets while HV connections are live (before the necessary degree of protection is no longer achieved).

5.1.2. High voltage shore supply system requirements

The requests listed below belong to the needs of the system on the shore side, where the requirements are grouped in two blocks:

5.1.2.1. Voltages and frequencies

- HVSC shall be provided with a nominal voltage of 6.6 kV AC and/or 11 kV AC, galvanically separated from the shore distribution system, in order to allow the standardization of the high-voltage shore supply in different ports; this galvanic separation on shore may be omitted if it is provided on board.
- The operating frequencies (50 or 60 Hz) of the ship and shore electrical systems shall match; otherwise, a frequency convertor may be utilized on shore.
- At the connection point, looking at the socket/connector face, the phase sequence shall be L1-L2-L3 or A-B-C or R-S-T. Phasors must rotate counter clockwise in reference to fixed observer, in order to produce a clockwise indication on the phase sequence indicator.

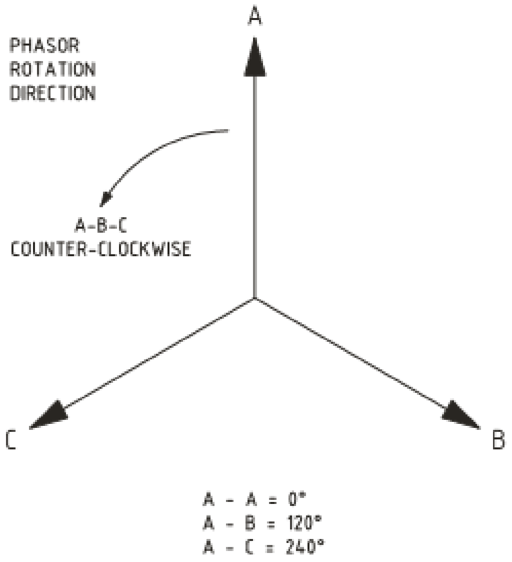

Figure 28: Phase sequence rotation, positive direction [3]

- The three-phase voltages must be balanced in time domain.

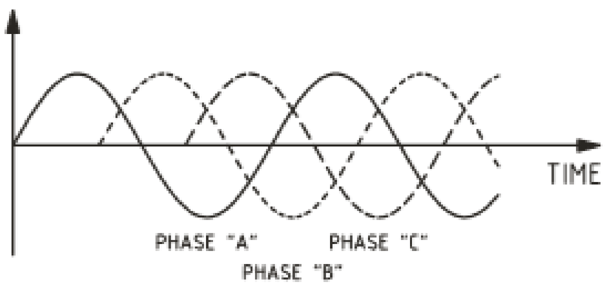

Figure 29: Balanced three-phase variables in time domain [3]

5.1.2.2. Quality of high voltage shore supply

- The high voltage shore supply system shall have a documented voltage supply quality specification.
- Shore supplies must be able to comply with the following maximum distortion characteristics, which shall be verified. These parameters shall be measured at the supply point:
  - Voltage and frequency tolerances (continuous):
    - The frequency shall not exceed the continuous tolerances ±5% between no-load and nominal rating;
    - For no-load conditions, the voltage at the point of the shore supply connection shall not exceed a voltage increase of 6% of nominal voltage;

        - For rated load conditions, the voltage at the point of the shore supply connection shall not exceed a voltage drop of -3.5% of nominal voltage.
    - Voltage and frequency transients:
        - The response of the voltage and frequency at the shore connection when subjected to an appropriate range of step changes in load shall be defined and documented for each high voltage shore supply installation;
        - The maximum step change in load expected when connected to a high voltage shore supply shall be defined and documented for each ship. The part of the system subjected to the largest voltage dip or peak in the event of the maximum step load being connected or disconnected shall be identified;
        - Comparison of the two points above shall be done to verify that the voltage transients limits of voltage +20% and -15% and the frequency transients limits of ±10%, will not be exceeded.
    - Harmonic distortion:
        - For no-load conditions, voltage harmonic distortion limits shall not exceed 3% for individual harmonic and 5% for total harmonic distortion.

5.1.3. Shore side installation

The following requirements are for the equipment on the shore side, which form the system able to provide the above specified voltages and frequencies. These requirements may be divided by the elements to which they refer.

5.1.3.1. System component requirements

- Circuit breaker and earthing switch:
    - The rated making capacity shall not be less than the prospective peak value of the short-circuit current;
    - The rated short-circuit breaking capacity of the circuit breaker shall not be less than the maximum prospective symmetrical short-circuit current;
    - An automatic operated circuit-breaker shall be provided.
- Transformer:
    - If adjustments are required to maintain the high voltage supply voltage within tolerances under load, then these adjustments shall be automatically controlled;

    - Transformers shall be of the separate winding type for primary and secondary side. The secondary side shall be star-configuration with neutral bushings (Dyn);
    - The temperature of supply-transformer windings shall be monitored, and in the event of over temperature, an alarm signal shall be transmitted to the ship;
    - Short circuit protection for each supply transformer shall be provided by circuit-breakers or fuses in the primary circuit and by a circuit breaker in the secondary. In addition, overload protection shall be provided for the primary and secondary circuit.
- Neutral earthing resistor:
    - The neutral point of the HVSC system transformer supplying the shore-to-ship power receptacles shall be earthed through either:
        - A neutral earthing resistor;
        - A neutral earthing resistor or through an earthing transformer with resistor on the primary side that provides an equivalent earth fault impedance, in cases where a frequency conversion is required.
    - The neutral earthing resistor rating in amperes shall not be less 1.25 times the preliminary system charging current. The rating shall be minimum 25 A DC.
    - The continuity of the neutral earthing resistor shall be continuously monitored. In the event of loss of continuity the shore side circuit breaker shall be tripped.
    - An earth fault shall not create a step or touch voltage exceeding 30 V at any location in the shore to ship power system.

5.1.3.2. High voltage interlocking

- Handling of high voltage plug/socket-outlets:
    - Handling of high voltage plug/socket-outlets shall only be allowed when the associated earthing switches on both ship and shore sides are closed;
    - Handling of the shore-side plug/socket-outlets shall only be possible when the shore-side earthing switch is closed.
- Operating of the high-voltage circuit breakers, disconnectors and earthing switches:
    - The circuit breakers cannot be closed in any of the following conditions:
        - One of the earthing switches is closed (shore-side/ship-side);
        - The pilot contact circuit is not established;
        - Emergency stop facilities are activated;
        - Ship or shore control, alarm or safety system self-monitoring diagnostics detect an error that would affect safe connection;
        - The communication link between shore and ship is not operational, where applicable;
        - The permission from the ship is not activated;

- The high voltage supply is not present;
- Equipotential bonding is not established.

  - Arrangements shall be provided so that the disconnector cannot be closed, or the circuit breaker cannot be racked into the service position, in any of the next conditions:
    - One of the earthing switches is closed (shore side/ship side);
    - The pilot contact circuit is not established;
    - The communication link between shore and ship is not operational, where applicable;
    - Equipotential bonding is not established.

5.1.3.3. Shore connection convertor equipment

- General:
  - The converting equipment shall be constructed, designed and tested according to the corresponding rules:
    - IEC 60076 for transformers;
    - IEC 60146-1 for semiconductor convertors;
    - IEC 60034 for rotating convertors;
    - IEC 61936-1 for the degree of protection for the electrical equipment.
  - Transformer winding and semiconductor or rotating convertor temperatures shall be monitored and an alarm shall be activated if the temperature exceeds a predetermined safe value.
- Cooling:
  - Where forced or closed circuit cooling is used, whether by air or with liquid, an alarm shall be initiated when the cooling medium exceeds a predetermined temperature and/or flow limits.
- Protection:
  - In the event of overload, an alarm signal shall be activated. This alarm shall be activated at a lower overload level than the circuit-breaker protection.
  - Alarms from the onshore protection equipment shall be transmitted to the ship.

5.1.4. HVSC system control and monitoring

The system both on shore and ship sides must be controlled and monitored according to the following requirements:

- General:
  - If the shore supply fails for any reason, supply by the ship's own generators is permitted, after disconnecting shore supply.

  - Load transfer shall be provided via blackout or automatic synchronization.
- Load transfer via blackout:
  - Interlocking means shall be provided so that the shore supply can only be connected to a dead switchboard. The interlocking means shall be arranged to prevent connection to a live switchboard when operating normally or in the event of a fault.
  - The simultaneous connection of a high voltage shore supply and a ship source of electrical power to the same dead section of the electrical system shall be prevented.
- Load transfer via automatic synchronization:
  - High voltage shore supply and ship sources of electrical power in temporarily parallel shall be in accordance with:
    - load shall be automatically synchronized and transferred between the HV shore supply and ship sources of electrical power following their connection in parallel;
    - The load transfer shall be completed in the shortest time practical without causing machinery or equipment failure or operation of protective devices and this time shall be used as the basis for defining the transfer time limit;
    - Any system or function used for paralleling or controlling the shore connection shall have no influence on the ship's electrical system, when there is no shore connection.
  - Where operation of only designated or a restricted number of ship sources of electrical power are required to permit the safe transfer of load between a high voltage shore supply and ship sources of electrical power, the arrangements shall fulfill this requirement before and during parallel connection.
  - If the defined transfer time limit for transferring of load between high voltage shore supply and ship sources of electrical power is exceeded, one of the sources shall be disconnected automatically activating an alarm. Special care shall be taken not to exceed the maximum permissible load steps of the generator sets.

5.1.5. Additional requirements for cruise ships

Besides all the mentioned above, there are some extra requirements for HVSC that are going to connect with cruise ships, like this case. Such requirements are the following:

5.1.5.1. Electrical requirements

- The HVSC system shall be rated for at least 16 MVA (but 20 MVA is recommended where practical) at nominal ship system voltages of 11 kV AC and/or 6.6 kV AC.
- The prospective short-circuit contribution level from the high voltage shore distribution system shall be limited by the shore-sided system to 25 kA rms.

5.1.5.2. Shore side installation

- The shore side transformer star point shall be earthed, through a neutral earthing resistor of 540 ohms continuous rated, and bonded only to the shipside.
- Each 3-phase HV plug or socket-outlet shall have:
    - Three phase current carrying contacts, (L1, L2, L3);
    - One earth contact;
    - One pilot contact for ground-check monitoring.

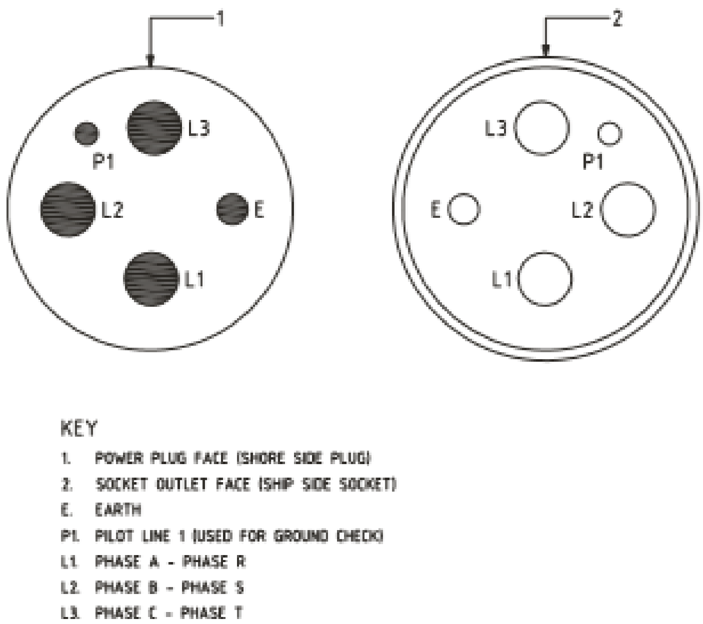

Figure 30: Shore power connector [3]

- Size, quantity and rating of cables shall be sufficient to meet the maximum power rating and voltage that the terminal can supply to the ship.
- The maximum short-circuit current is 25 kA / 1 s and a maximum peak short-circuit current of 63 kA.
- The power plugs as well as the neutral plug shall be fitted with fail-safe limit switches that are activated only when the plug and socket-outlet are properly mated. These fail safe limit switches shall be activated in the emergency shutdown.

5.2. Summary of main requirements

Besides all the requirements explained up to this point, the standard includes many more, mainly related to the ship side of the installation, the connection cable and the interface, which are not elements of interest in this project.

Mostly, the requirements that the standard sets are safety-related measures, not only for the safety of the system itself, but for everybody that might be near or in contact with it. In this summary, attention will be paid to the requirements that affect the parameters of the circuit, in order to define the limits that values like the voltage or the current may have.

Divided in different conditions, the main requirements affecting the values of the system are the following.

5.2.1. Normal conditions

There are some quality requirements that the current going through the system must fulfill always that it is working without problems. These can affect different parameters.

Voltage:

- The high voltage shore supply and link nominal voltage is of 6.6 kV or 11 kV AC.
- The HVSC system shall be rated for at least 16 MVA, but 20 MVA is recommended.
- When it is DC:
    - For no-load conditions, the voltage at the point of the shore supply connection shall not exceed a voltage increase of 6% of nominal voltage
    - For rated load conditions, the voltage at the point of the shore supply connection shall not exceed a voltage drop of -3.5% of nominal voltage.
- When there is a number of step changes in load (transient conditions):
    - Transient limits are of +20% and -15%.
- In harmonic distortion:
    - For no-load conditions, voltage harmonic distortion limits shall not exceed 3% for individual harmonic and 5% for total harmonic distortion.

Frequency:

- The operating frequencies must be of 50 or 60 Hz.
- When it is DC:
    - The frequency shall not exceed the continuous tolerances ±5% between no-load and nominal rating.
- When there is a number of step changes in load (transient conditions):
    - Transient limits are of ±10%.

5.2.2. Short circuit case

The possibility that a short circuit happens in the system is real, and it probably will occur in the connection of the ship with the rest of the circuit. For these circumstances, there are also some requirements stablished by the standard:

Current:

- The maximum short-circuit current in the system should be limited to 16 kArms during 1 second, as a general rule. Although, for cruise ships it shall be limited to 25 kArms during 1 second.
- The maximum short-circuit peak shall be of 40 kA, but as cruise ships have special requirements, the maximum peak short-circuit current allowed is of 63 kA.

6. Shore connection design process

In this chapter it is going to be shown how all the previously explained components are combined and organized in order to complete the mission of the HVSC with success. The aim is to provide to the various ships berthed at the piers an electricity of quality, with as few oscillations as possible, so the parameters of all elements must be properly adjusted. Also, the frequency and the voltage that the ship's grid will receive will be different from the ones of the source. Thereby, more parameters will have to be taken into account.

Theoretically, this system should be able to supply energy to various ships at the same time. To run the simulations of the performance of the circuit the number of ships has to be small, otherwise it will last a too long time. For this reason, the system is going to be designed to supply four ships, each one with the characteristics of power alimentation of the Figure 31:

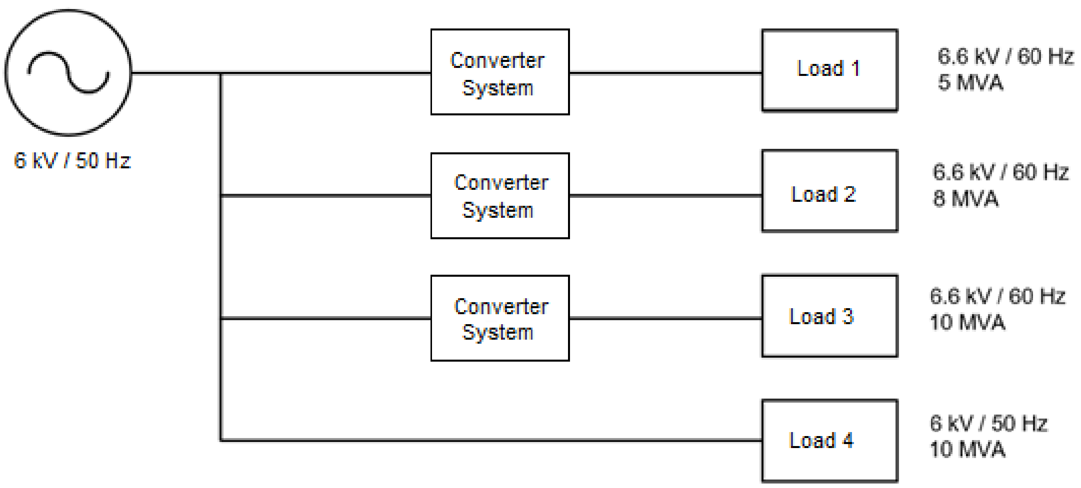

Figure 31: Requirements of the ships

As it can be seen, there are three ships that need a frequency of 60 Hz and 6.6 kV of average voltage, while they are equivalent to loads of 5, 8 and 10 MVA respectively. For these ones, a conversion of the frequency must be done. The voltage must be adapted too. But the fourth ship works with a frequency of 50 Hz, so no transformation is needed. Meanwhile, the value of the voltage is the same that the provided by the source.

With all these considerations explained, now the detailed design process of the HVSC with Matlab Simulink will be described.

The design of the system will be explained basically moving from left to right: while in the left end there is the source, the right end is formed by the loads that represent the ships. Besides the displacement from left to right, there is the fact that the system is formed by smaller blocks called subsystems. Every time that one of these is found, its internal distribution will be explained following the same path.

Although the description of the system will be focused on the final version of the elements that form it, in some cases also a bit of the previous versions will be explained.

6.1. Source

The first element and the most important one (without it, there would not be any electricity to make the system work) is the power source. It must be a three-phase AC source, as it has already been specified, and connected to the ground. The outputs A, B and C are the three phases, which will lead to the rest of the system.

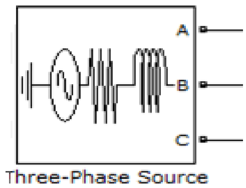

Figure 32: Three-phase source

The parameters of the source are the frequency of 50 Hz of the electrical national grid, and the phase to phase voltage, which has to be adjusted in order to obtain the desired voltage at the output of the source. In this case it is required a RMS voltage of 6,000 Vrms, so the phase to phase voltage necessary to reach this value is 6,641 Vrms, as tests have demonstrated. Other parameters are the three-phase short-circuit level at base voltage and the base voltage: in this case, they are respectively of $250x10^6$ VA and $6x10^3$ Vrms.

The source is the only common element for the subsystems that connect with all four ships. That is why the next element is located in the wiring that connects the source with only one ship.

6.2. Ship subsystem

The ship subsystem is the set of blocks where the proper circuit that does all the conversion of voltage and frequency for supplying one ship is found. That means that the basic structure of this subsystem is the already mentioned rectifier-DC link-inverter, but it must be taken into account that the transformer is also included here. Meanwhile, the rectifier and the inverter are subsystems themselves, and they must be designed accurately.

6.2.1. Transformer

The transformer of the subsystem is three-phased and of three windings. This kind of transformer has the characteristics explained in a previous chapter, and each one of the windings must have its configuration, star (Y) or delta (Δ), selected on the dialog box of the block:

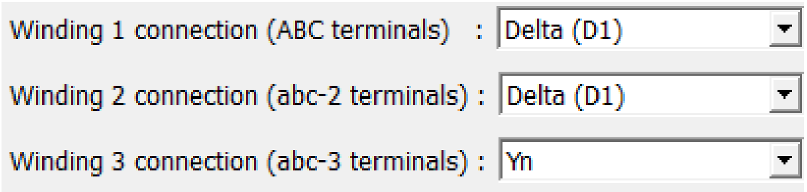

Figure 33: Configuration of the transformer's windings

In this case, the configurations of windings 1 and 2 are delta, while the winding 3 has a star connection. This combination should allow the stability of the system and its results.

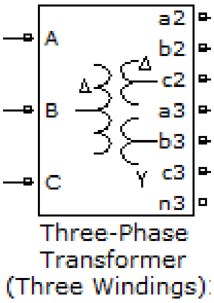

Figure 34: Three-phase transformer

The internal parameters of the transformer have to be specified. The nominal power is of $10x10^9$ VA, while the frequency is still of 50 Hz. On the winding of the source side (winding 1) it is easy to establish the voltage, as it must be the same 6,000 Vrms of the three-phase source. On the other hand, the voltages of windings 2 and 3 are not specified, but there has to be found a value for them that makes possible to have the Vrms required value of 6.6 kV to supply the ships.

In order to do so, different values for the windings voltages have to be tested, once the whole system is finished, until it is found that the ships receive the right voltage. But first, the internal resistances and inductances of the transformer must be also modified, so it is possible to reach the desired voltage.

In each winding of each transformer, the internal resistance will have a value of 0.001 Ohm and the internal inductance will be of 0.01 H. For the Vrms of each transformer, depending on the load of the ship that it is supplying, the value will be:

Ship	Winding Voltage (Vrms)
5 MVA - Ship 1	5,570
8 MVA - Ship 2	6,700
10 MVA - Ship 3	7,800

Table 6: Winding voltages of the transformers

6.2.2. Rectifier

The wires that go out of the transformer reach directly the rectifier. This element is also a subsystem, where the energy comes in in the shape of an AC and comes out as DC.

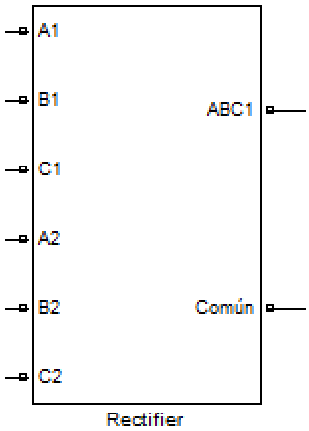

Figure 35: Subsystem rectifier

There has been a path to implement this block, as it was not done in one step. Before having the final version, some tests were done in Matlab Simulink with different configurations of rectifiers. First, the behavior of single-phase rectifiers was studied, and the results of having more or less diodes in the circuit were compared.

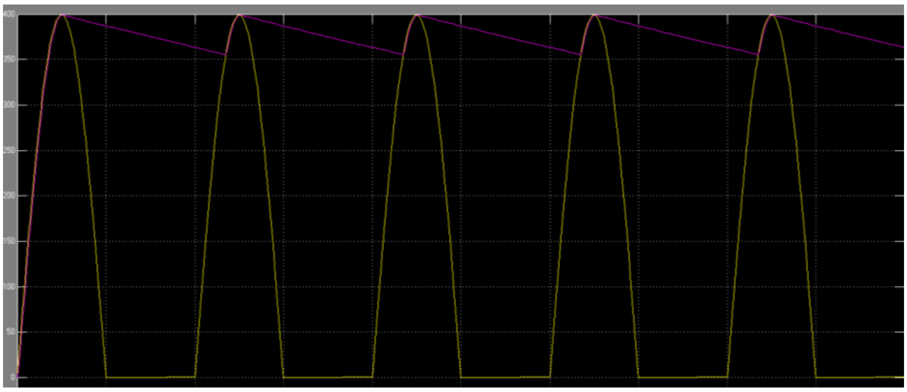

Figure 36: Voltage of single-phase rectifier with one diode

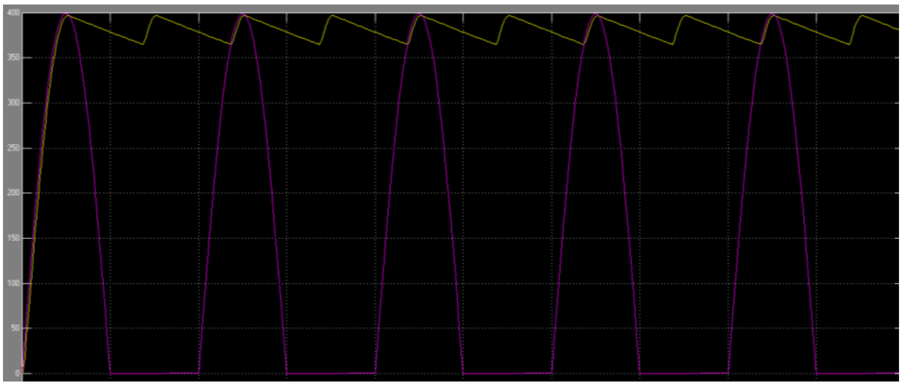

Figure 37: Voltage of single-phase rectifier with four diodes

After that, the tests were upgraded to three-phase systems and also the results of using three, six and twelve diodes were compared.

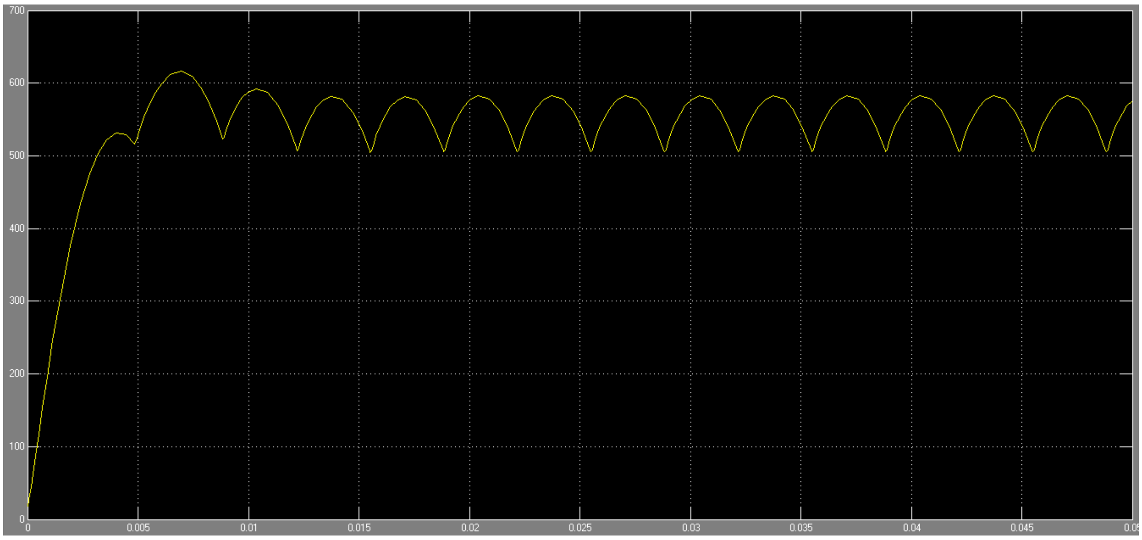

Figure 38: Voltage of three-phase rectifier with six diodes

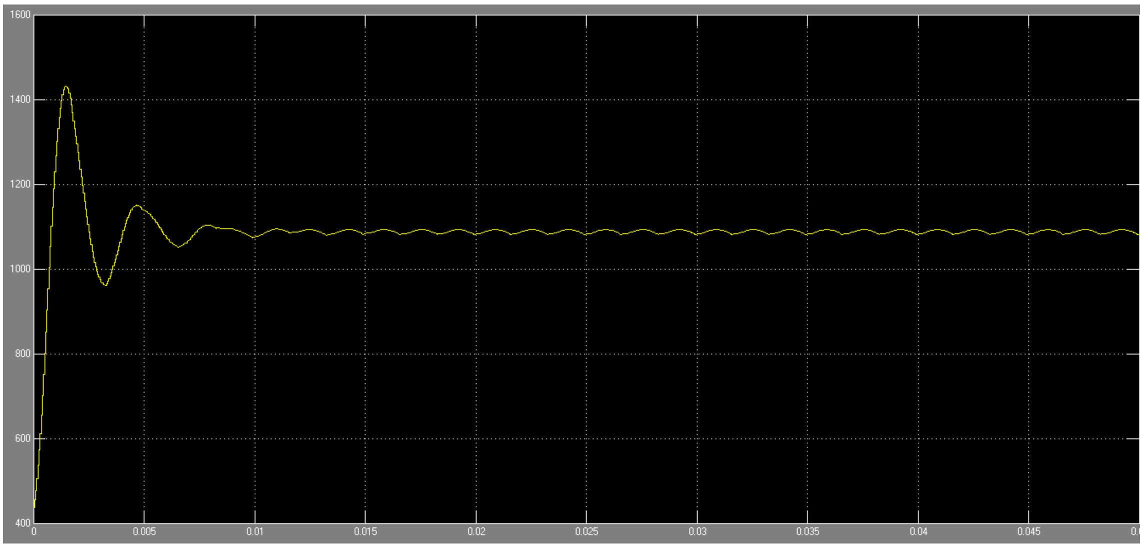

Figure 39: Voltage of three-phase rectifier with twelve diodes

As it was expected, the one that gave better results and a straighter output was the rectifier of twelve diodes, so it was decided that one of this kind was going to be implemented in the final design.

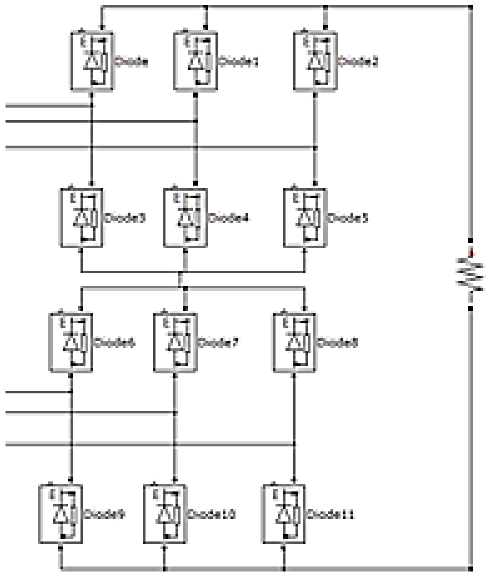

Figure 40: Three-phase rectifier with twelve diodes

But before implementing this version in the HVSC circuit, it was taken into account that the block of the universal bridge can represent up to six diodes. Therefore, using it would make the rectifier look clearer and simpler:

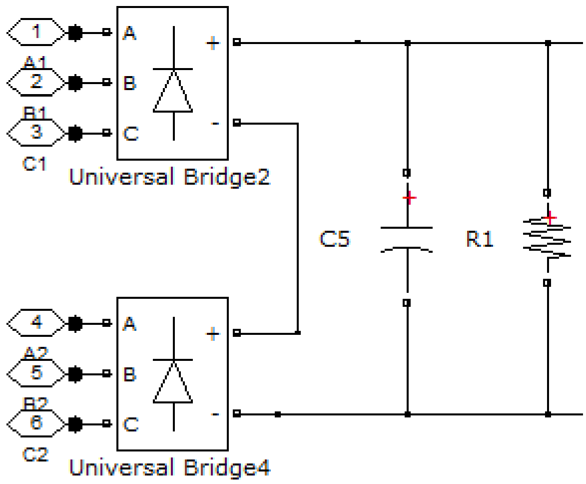

Figure 41: Three-phase rectifier with twelve diodes using universal bridges

The parameters of the capacitance and the resistance that complement the bridge of diodes are adapted in order to obtain better results. In this case, the capacitance has a value of $5x10^{-4}$ F, and the resistance is of 1,000 Ohm.

6.2.3. DC link

The DC link is not an element, but the interphase between the rectifier and the inverter. Here, the current is momentarily DC, before being converted again into AC with a different frequency from the original. This link acts as a filter, softening the signal that is coming out from the rectifier.

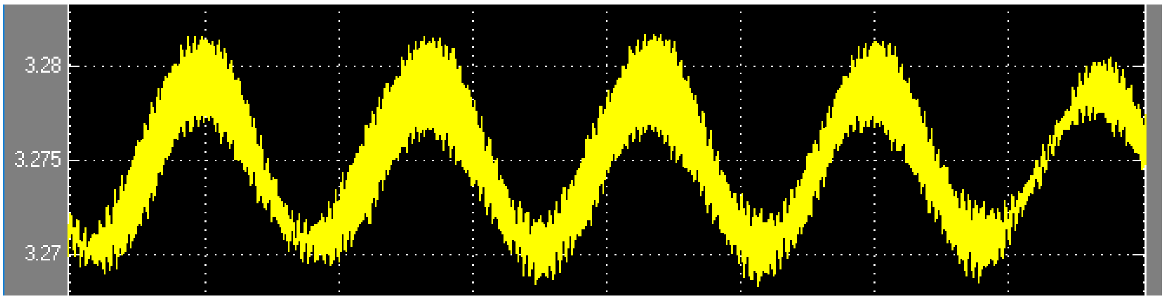

Figure 42: DC before the filter

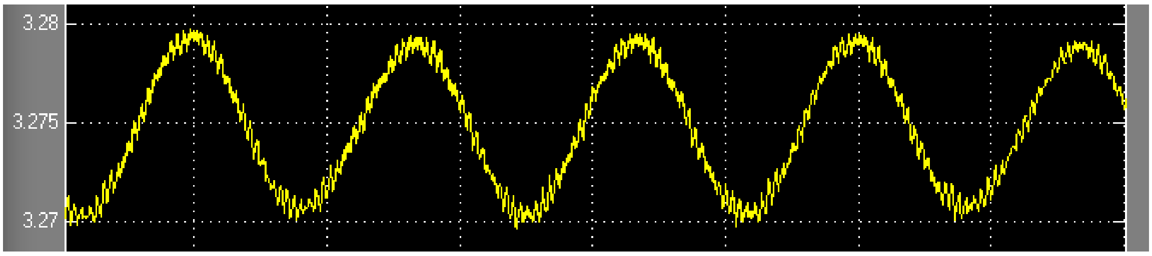

Figure 43: DC after the filter

To do this, the DC link has an inductance and a capacitance, set with the right parameters to obtain a good result.

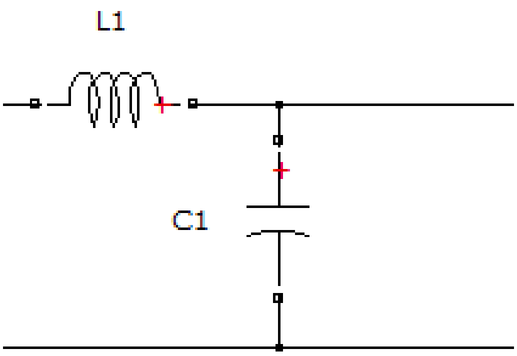

Figure 44: DC link

Here the inductance is of $10\text{x}10^{-7}$ H, while the capacitance has a value of $50\text{x}10^{-4}$ F.

6.2.4. Inverter

After being filtered by the DC link, the current reaches the inverter. Inside this block, which is actually another subsystem, all the present elements will combine them to create a new three-phase AC system.

Like in the rectifier's situation, the first version done of the inverter was far away from the finally implemented. In fact, the first tested was the first inverter example showed in the chapter describing the characteristics of the main components, the one of two levels controlled by pulse generators and DC sources of different voltages. Afterwards, that version was upgraded to a three level inverter, and later converted into a three-phase inverter thanks to adjusting the phase of all the six pulse generators in every subsystem (where each subsystem is responsible of generating one phase of a three-level AC wave) of the following figure:

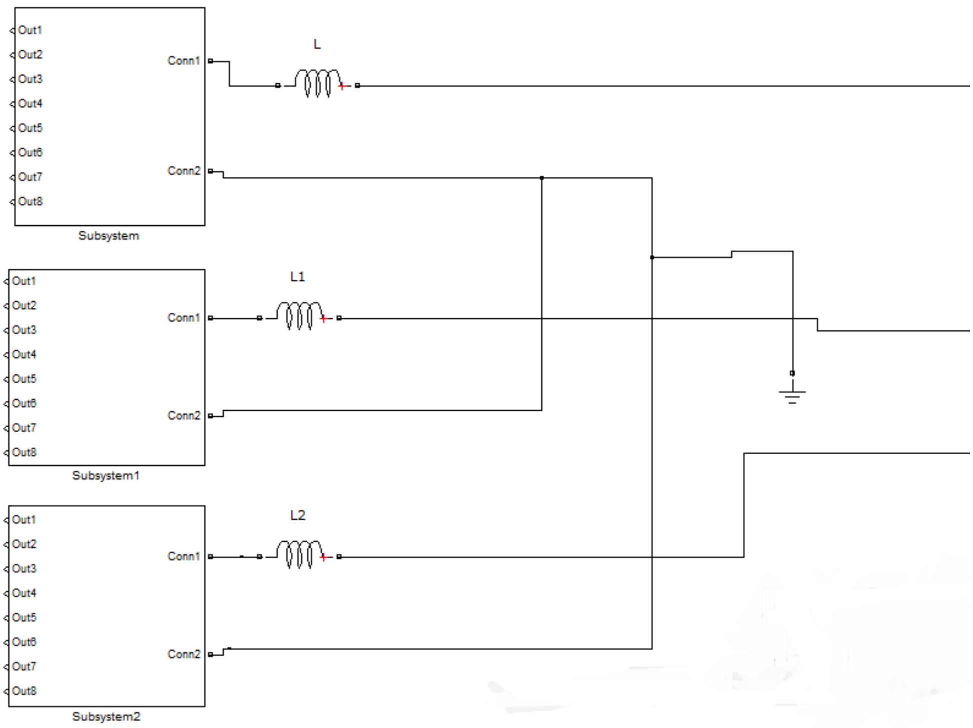

Figure 45: Generating subsystems of levels in a three-phase inverter

Although, then it was observed that controlling the inverter with independent generated pulses and through different levels of voltage was harder than initially expected, as the current coming from the rectifier had a single, constant voltage value. So, the idea of using a bridge of interrupters with six switches was introduced:

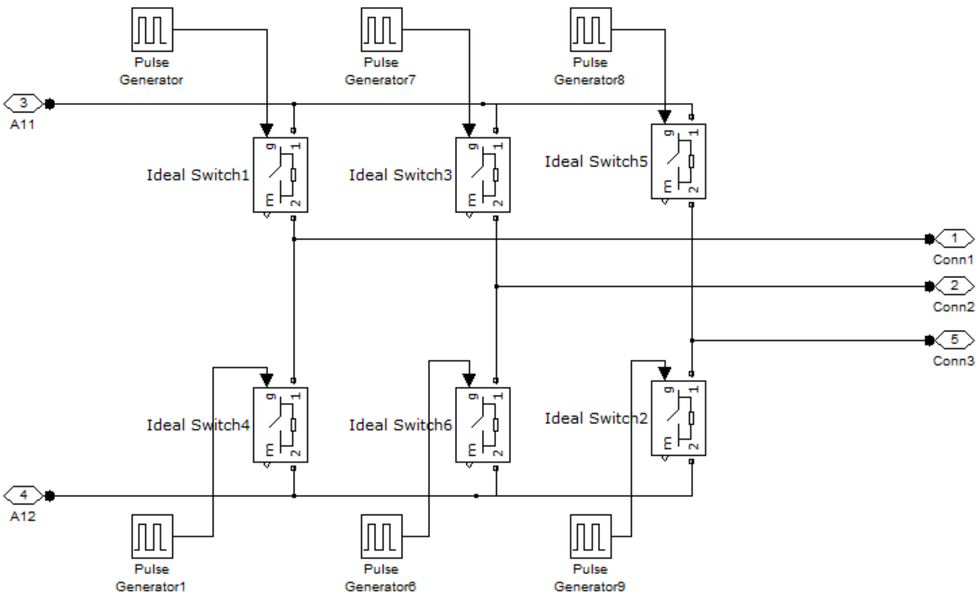

Figure 46: Inverter with six interrupters activated by pulses

With that circuit (and one impedance on each phase) the result of the following figure was obtained. Although it was good as a first approximation, changes had to be introduced in order to obtain a better accuracy.

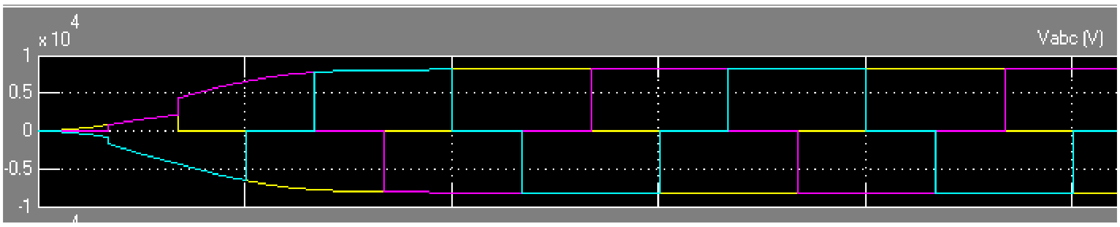

Figure 47: Voltage result of an inverter with six interrupters activated by pulses

The first change was to substitute the ideal switches for IGBT/Diode elements, and then the PWM was introduced to obtain the following definitive circuit design.

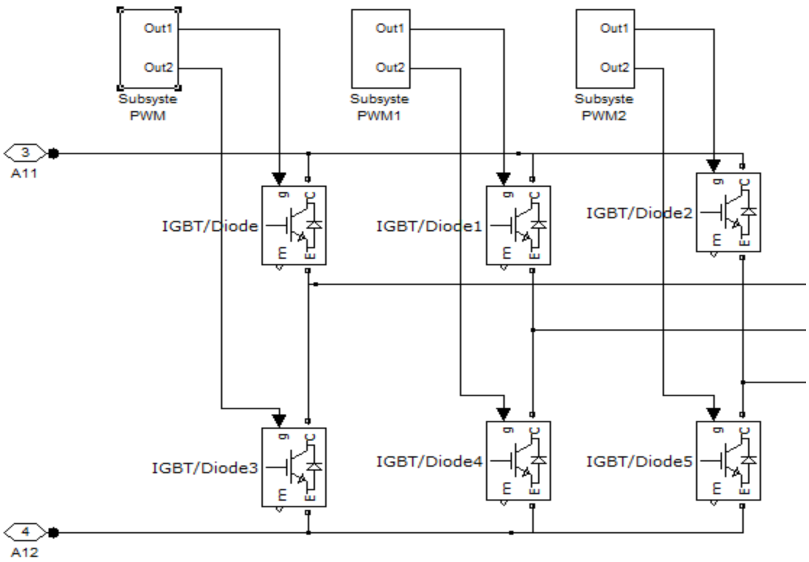

Figure 48: Inverter with six interrupters activated by PWM

6.2.4.1. Pulse-Width Modulation

The block of the PWM is another subsystem inside the component where the bridge of IGBT is found (which is actually a subsystem of the inverter). The operation of the PWM has been already explained, so the elements that form it must be introduced in Matlab Simulink and combined to obtain the right results.

First, a triangular signal is needed. This wave must have a high frequency, and like the period is the parameter asked, the value will be of 0.0005. Another parameter asked to define this signal is the range of output values, which will be defined between -1 and 1.

Second, the sine wave must be introduced. In this one, the parameters asked are the amplitude of the wave, which here is set at 0.95. Also the frequency must be specified. As this frequency is the one that will have the resulting three-phase current, it must be of 60 Hz. However, Matlab Simulink is asking for it in rad/s, so the following transformation must be done:

$$Frequency = 60\ x\ (2\ x\ \pi) = 377\ {}^{rad}/_{s}$$

The last parameter that has to be defined to create later a correct PWM is the phase. When it is a single-phase system it is 0, but as this is a three-phase system and it will have three non-connected PWM generators, each sine wave must have a phase of 120º with the other two. As Matlab Simulink is not asking for this phase in degrees but radians, a conversion has to be done again:

$$0º = 0\,rad$$

$$120º = \frac{120\ x\ \pi}{180} = 2.0944\,rad$$

$$240º = \frac{240\ x\ \pi}{180} = 4.18879\,rad$$

Once the two waves that are going to be compared are introduced and their parameters are correctly adjusted, it is time to integrate the relational operator that is going to compare the two waves. Concretely, it will be the block “<=”: it has two inputs, where the two waves are connected, and one Boolean output, as it will only take the values of true (1) or false (0). In this case, the output will be 1 when the first input (triangular wave) is lower than the second input (sine wave): while this is happening, the IGBT that is receiving this signal will be working and allowing the current to flow. Otherwise, when the triangular wave is higher than the sine wave, the output will take the value 0 and the connected interrupter will be opened.

These three blocks combined allow sending a signal to control one IGBT, but it has already been explained that every half-bridge consists of two interrupters. These interrupters must have opposed states all the time, because having them both closed would cause major issues such as a short circuit. The best way to solve this is to generate the opposite signal of the first one. This can be done simply by adding a constant with a value of 1 to the subsystem, connected to a sum block where the output signal of the relational operator is subtracted from the constant. As a result, a second signal will be generated, and it will be 0 exactly when the first signal is 1, and vice versa.

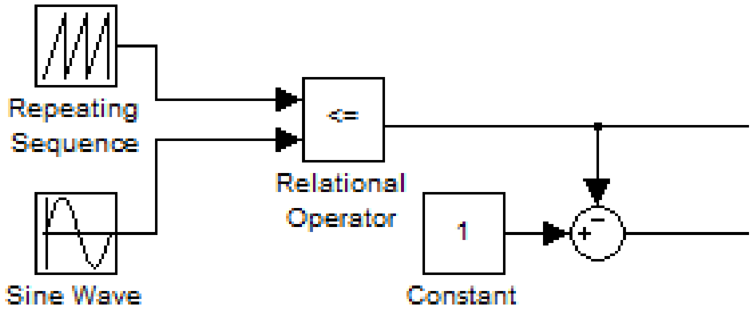

Figure 49: Generation of PWM signals

This generation of the auxiliary PWM signals will be closed into one subsystem, and then connected to the gates of the two corresponding IGBT.

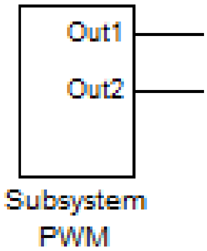

Figure 50: Subsystem generating the PWM signals

6.2.4.2. Generation of three-phase AC

Just like the generation of the PWM signals is a subsystem connected to the IGBT, also the whole bridge of interrupters (and consequently, the PWM subsystems that activate them) is found in one subsystem called Pulses. Before this system, the electricity is in DC; after, it is again AC and has the frequency of 60 Hz needed to supply the network of the connected ship. Even so, it is not ready yet to reach the ship, because it still has the shape of the PWM:

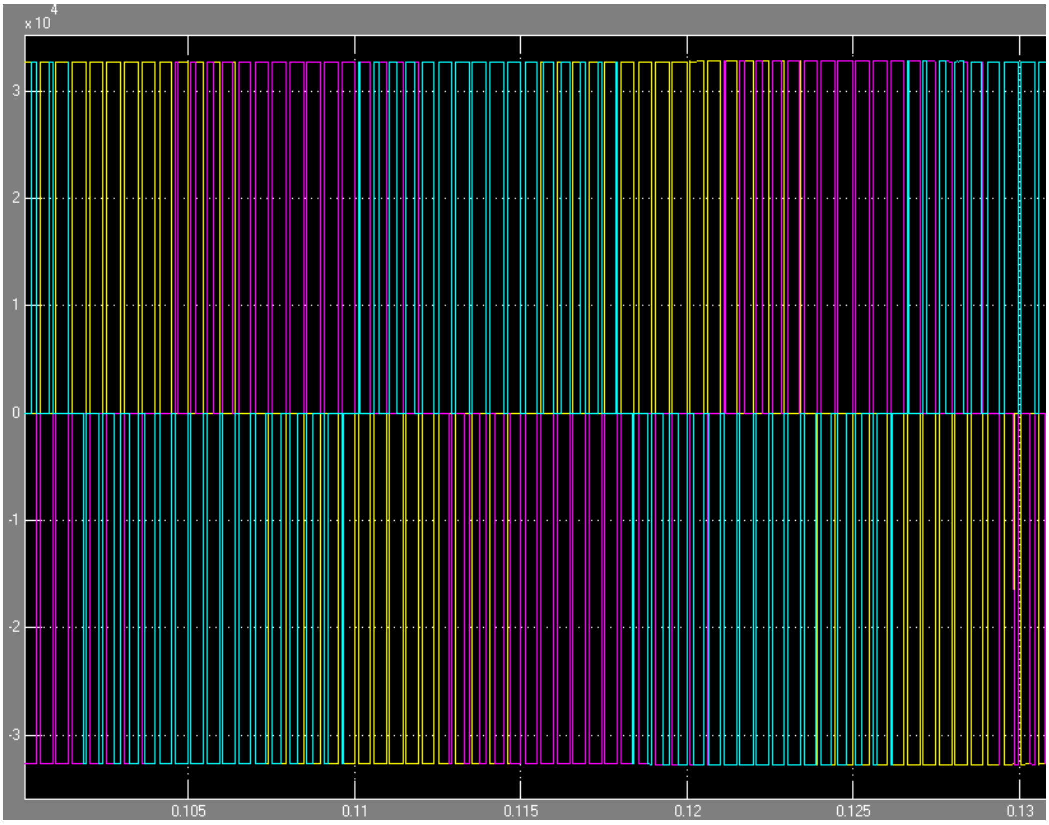

Figure 51: Voltage after of the inverter

The way to solve this is by using an inductance in each one of the phases.

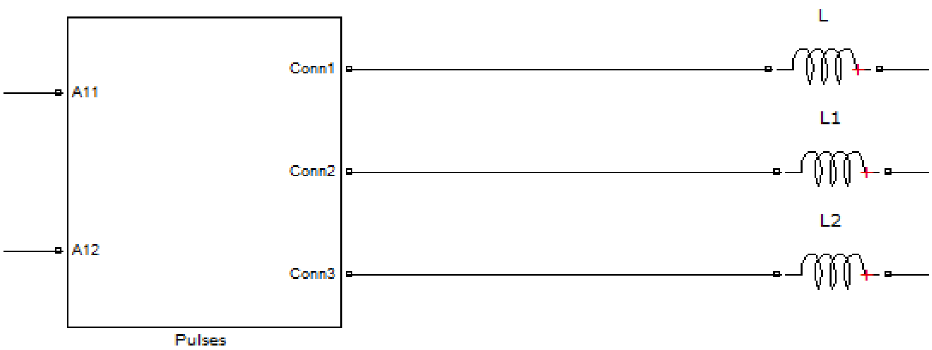

Figure 52: Inverter with inductances

With an inductance value of $50x10^{-4}$ F, the three-phase signal that comes out from the Pulses subsystem has the following aspect after going through them:

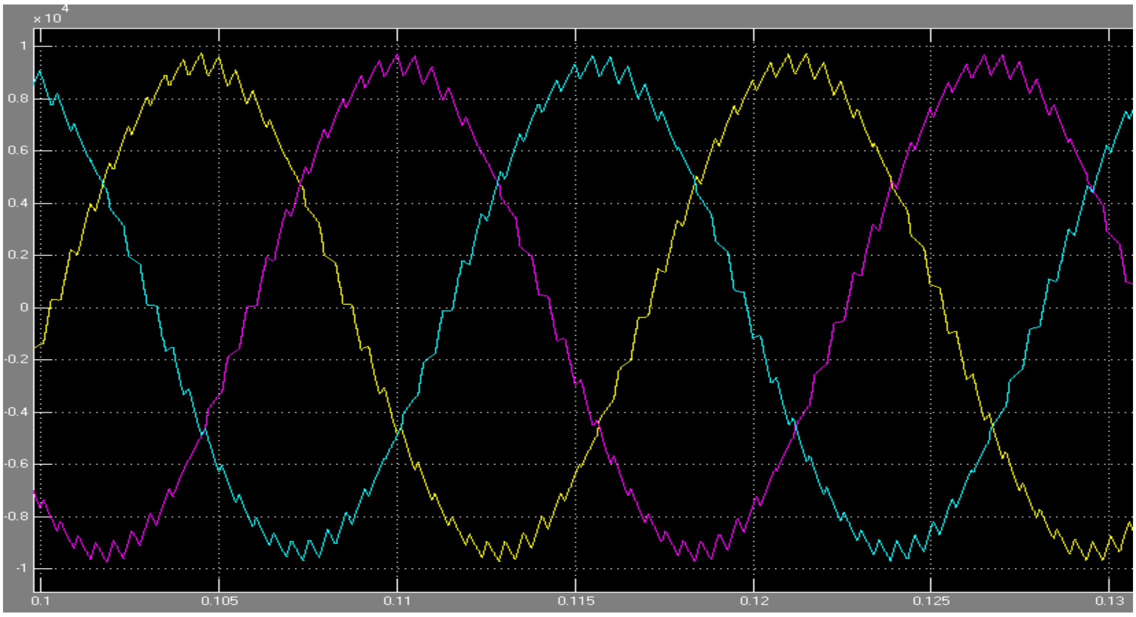

Figure 53: Voltage after the inductances of the inverter

All this is included in the Inverter subsystem. At the exit of this block, the current is ready to reach the ship in good quality conditions.

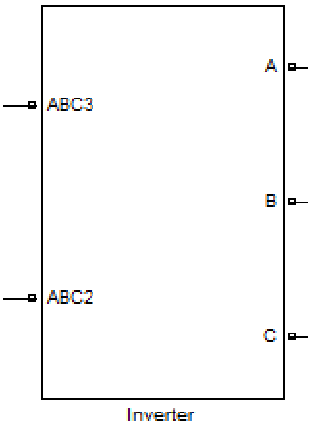

Figure 54: Subsystem inverter

6.2.5. One ship system

Once each one of the previous blocks and elements have been designed, it is time to join them all. Together, the transformer, the rectifier, the DC link and the inverter will form the subsystem that will be able to do the transformation of current and voltage for one ship, whatever are their requirements.

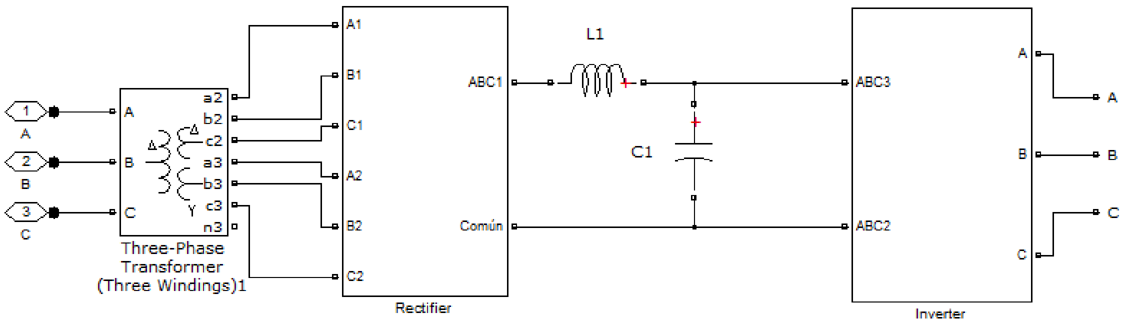

Figure 55: Converter system of one ship

6.3. Load

What is called the load is actually the block that is representing the ship berthed at dock. Here it is shown as a three-phase RLC load, where there is a part of resistance and another one of inductance:

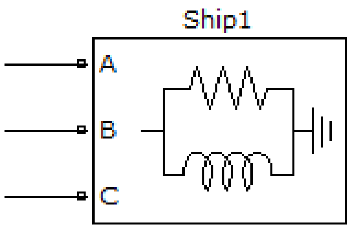

Figure 56: Load of one ship

There are four loads expected for this circuit, each one of them with a power factor (PF) of 0.8. Therefore, this factor must be taken into account to calculate the active and the reactive part of each load. The results are summed up in the next table:

PF=0.8	P (MW)	Q (MVar)
5 MVA	4	3
8 MVA	6.4	4.8
10 MVA	8	6

Table 7: Active and reactive power of each load

Besides the active and reactive part of the load, other parameters are asked to determine the load. Obviously, there is the frequency (in Hz) which must be 60 for the three first ships, and 50 for the last one. And also the nominal phase-to-phase voltage must be specified: in the three first cases, it is 6,600 Vrms; for the last ship, it is 6,000 Vrms.

The next table summarizes the right values for all the parameters of the four ships:

Ship	Power (MV)	P (MW)	Q (MVar)	Nominal voltage (Vrms)	Frequency (Hz)
1	5	4	3	6,600	60
2	8	6.4	4.8	6,600	60
3	10	8	6	6,600	60
4	10	8	6	6,000	50

Table 8: Main parameters of the four ships

6.4. Others

Besides the electrical components that form the system of the HVSC, there are other elements that are not strictly a part of the circuit. However, they are a vital part of the system, as they are able to facilitate the process of design, to introduce changes and to observe what is happening in the circuit.

6.4.1. Measuring elements

One of the most important groups of these elements is the formed by the measuring systems. In most of the figures previously shown of the different parts of the circuit the measuring elements have been hidden, just to make easier the interpretation of the images without possible confusions that could be caused by the measuring lines.

6.4.1.1. Voltage measurement

One of the most used measuring elements has been the Voltage measurement. This block measures the voltage between two phases, and its results can be seen through a scope.

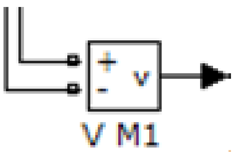

Figure 57: Voltage measurement block

6.4.1.2. Scope

In fact, the scope is definitely the most used of all the measuring blocks, as it is absolutely necessary to visualize the results. The scope may have one input or many more (up to five inputs have been used in the same scope in this project), and it will have as many axes as inputs.

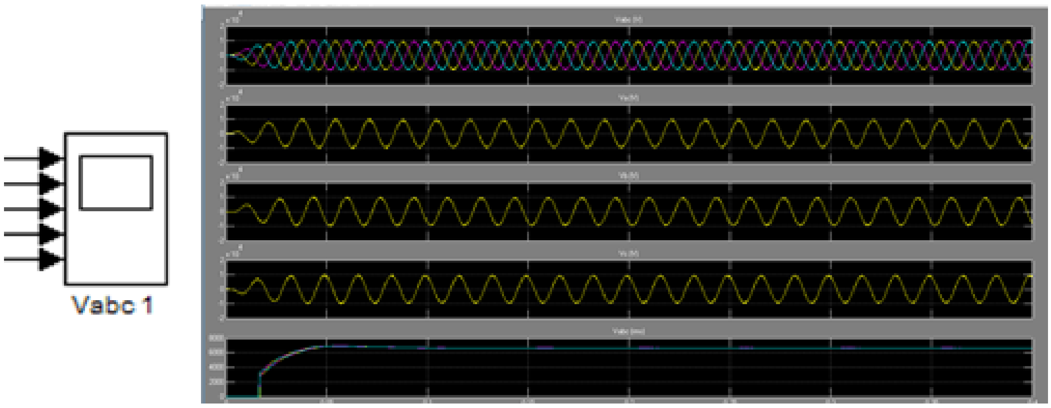

Figure 58: Scope block and visualization

6.4.1.3. RMS discrete

Other block used to do measurements is the RMS discrete: this one simply calculates the root mean square (RMS) of a signal. In this project, it is used to obtain the RMS voltage and the RMS current of each ship subsystem. Thanks to the image of the Vrms that it provides, it is possible to observe it when changes are done at the windings 2 and 3 of the transformer, in order to find the right value for the windings that creates a voltage of approximately 6,600 Vrms.

The only parameter that must be adjusted in this block is its fundamental frequency. For the measures in the subsystems of the three first ships, it must be 60 Hz. On the other hand, the fundamental frequency of this block situated in the ship 4 subsystem is of 50 Hz.

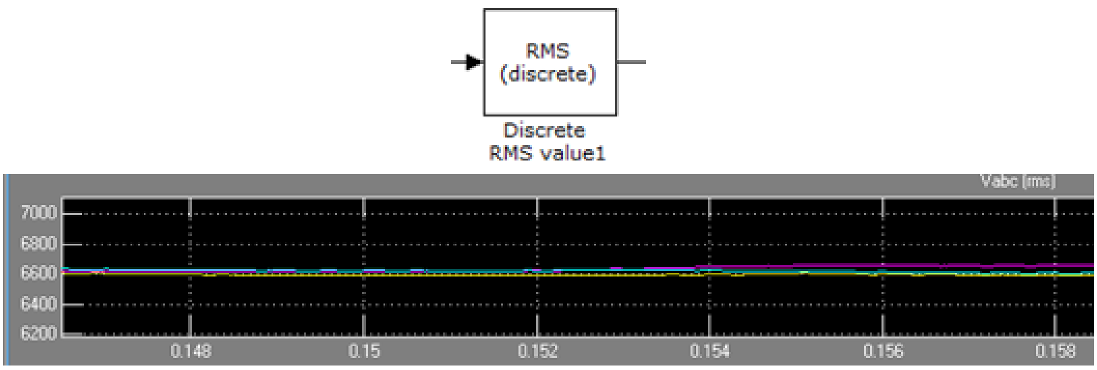

Figure 59: RMS discrete block and results

6.4.1.4. *Mean value*

Another one that can be found is the block of Mean value. The objective of this element is, as its own name says, to compute the mean value of the input signal, which in this project is the voltage between two phases, during a selected average period (which is the inverse of the 50 Hz frequency of the original AC).

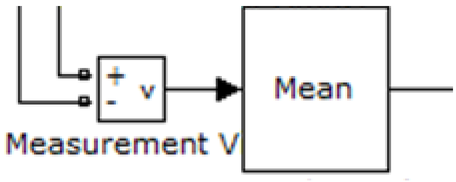

Figure 60: Mean value block

6.4.1.5. *Three-phase V-I measurement*

Finally, other measurement block with an especial relevance is the Three-phase V-I measurement. This one is used to obtain easily the value of the voltage and the current of a three-phase system, in a way that can be later separated into the three phases that conform the output, and also allowing calculating the RMS value thanks to the previously explained block.

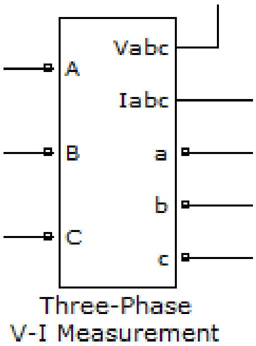

Figure 61: Three-phase V-I measurement block

In fact, the subsystem that connects the ship number four with the source consists only of measuring elements, as the alimentation of this ship is directly the one created by the source, without any alterations.

6.4.2. Powergui

The powergui is a necessary block to run the simulations. It is implemented as an isolated element next to the circuit, and it is used to configure the main parameters of the simulations that will be performed.

The simulation type is the most important parameter that must be selected. In this case, it will be Discrete. Choosing this option also appears the parameter of the sample time that must be taken for the simulations. A value of 10^{-5} seconds will be given.

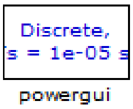

Figure 62: Powergui block

Besides choosing the simulation type, the powergui block may have other uses. For example, it is useful to see the measurements of all over the system, the values of the source or other parameters.

```
MEASUREMENTS:

  1:  'U System Ship 3/V M1                                  '  =       8485.28 V
  2:  'U System Ship 2/V M1                                  '  =       8485.28 V
  3:  'U System Ship 1/V M1                                  '  =       8485.28 V

NONLINEAR ELEMENTS (system outputs):

  1:  'U arm1 1: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V    -0.00°
  2:  'U arm1 2: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V   -60.00°
  3:  'U arm2 1: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V  -120.00°
  4:  'U arm2 2: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V   180.00°
  5:  'U arm3 1: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V   120.00°
  6:  'U arm3 2: System Ship 1/Rectifier/Universal Bridge2'  =     9961.28 V    60.00°
```

Figure 63: Measurements given by the powergui

6.4.3. Three-phase breaker

The three-phase breaker is an interrupter that acts in the three phases at the same time. It is a block used during the simulations to recreate the load changes. The initial state of the breaker can be either opened or closed and the moment changing from one state to other may be controlled, so it is possible to connect or disconnect an extra load to one electric feeder by controlling the breaker that leads to that load.

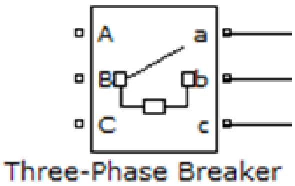

Figure 64: Three-phase breaker

6.4.4. Three-phase fault

The block of a three-phase fault creates a programmed short circuit in the electric feeders where it is connected. The parameters of this element allow selecting exactly how it is going to be the short circuit created. On one hand, it can be decided if the fault is going to be produced in the three phases at the same time, or if it is only going to affect one or two of them. But the most important is that it is possible to decide the moment when the short circuit is going to be produced, so the results that it causes can be properly analyzed.

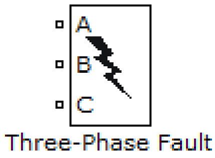

Figure 65: Three-phase fault

6.4.5. Script

A script is not an element, but a separate document where parameters of all blocks of the system can be listed, controlled and changed in a single place. It works giving a name to a specific parameter and then a value; when this parameter is asked in the dialog box of any block, what must be written is the name given to the parameter.

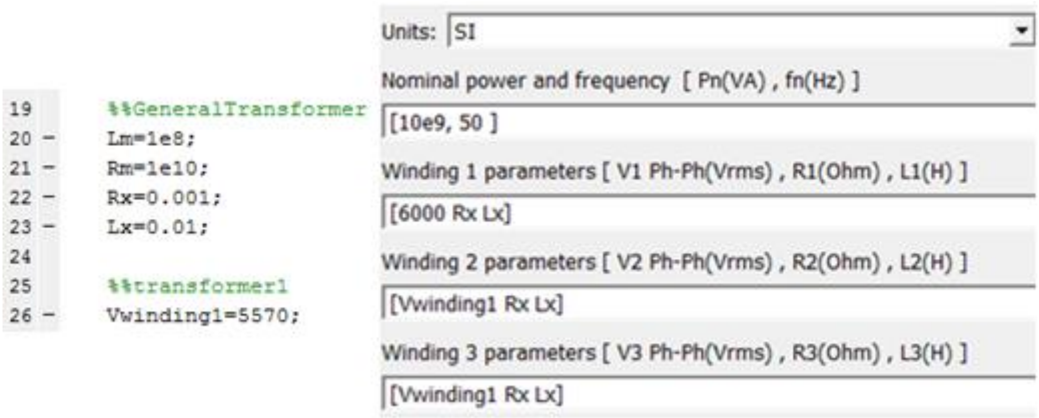

Figure 66: Example of use of the script

The script facilitates changing various parameters at the same time and in a faster way, as all of them can be seen in just one look instead of having to open the dialog boxes of the elements whose parameters have to be modified. In this project it is a very useful tool, because numerous tests changing parameters have been done. For example, it was used to adjust the windings of the transformers in order to obtain the right Vrms voltage in each ship; it was also helpful when the values of resistances, inductances and capacitances found in the rectifier, DC link and the inverter had to be studied and modified several times, with the goal of obtaining the best results.

6.5. Overall system

All the above mentioned elements and subsystems together create the HVSC circuit to simulate the system that supplies one ship. Joining all the phases, the resulting connection can be seen in the next figure:

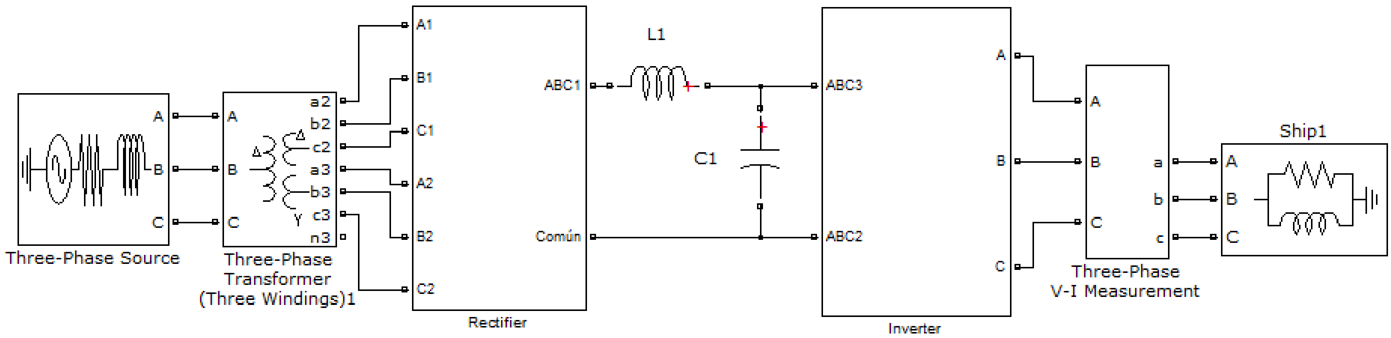

Figure 67: Connection of one ship

Nevertheless, the system is designed to be connected to four loads in parallel, so all the elements forming the converter system for one ship must be repeated to connect with the other loads.

Ships 2 and 3 work with the same frequency that ship 1, so the subsystem can be simply replicated twice and connected to each one of the new loads. The only changes that must be done are the values of windings 2 and 3 of the transformers, as they are the only parameters that change between these three ships.

As it regards the last ship, it works with 50 Hz and the same voltage directly produced by the source. As a consequence, there is no need to implement another subsystem to transform the energy. Therefore, the only thing that is going to be introduced between the source and the fourth ship is a set of measuring elements.

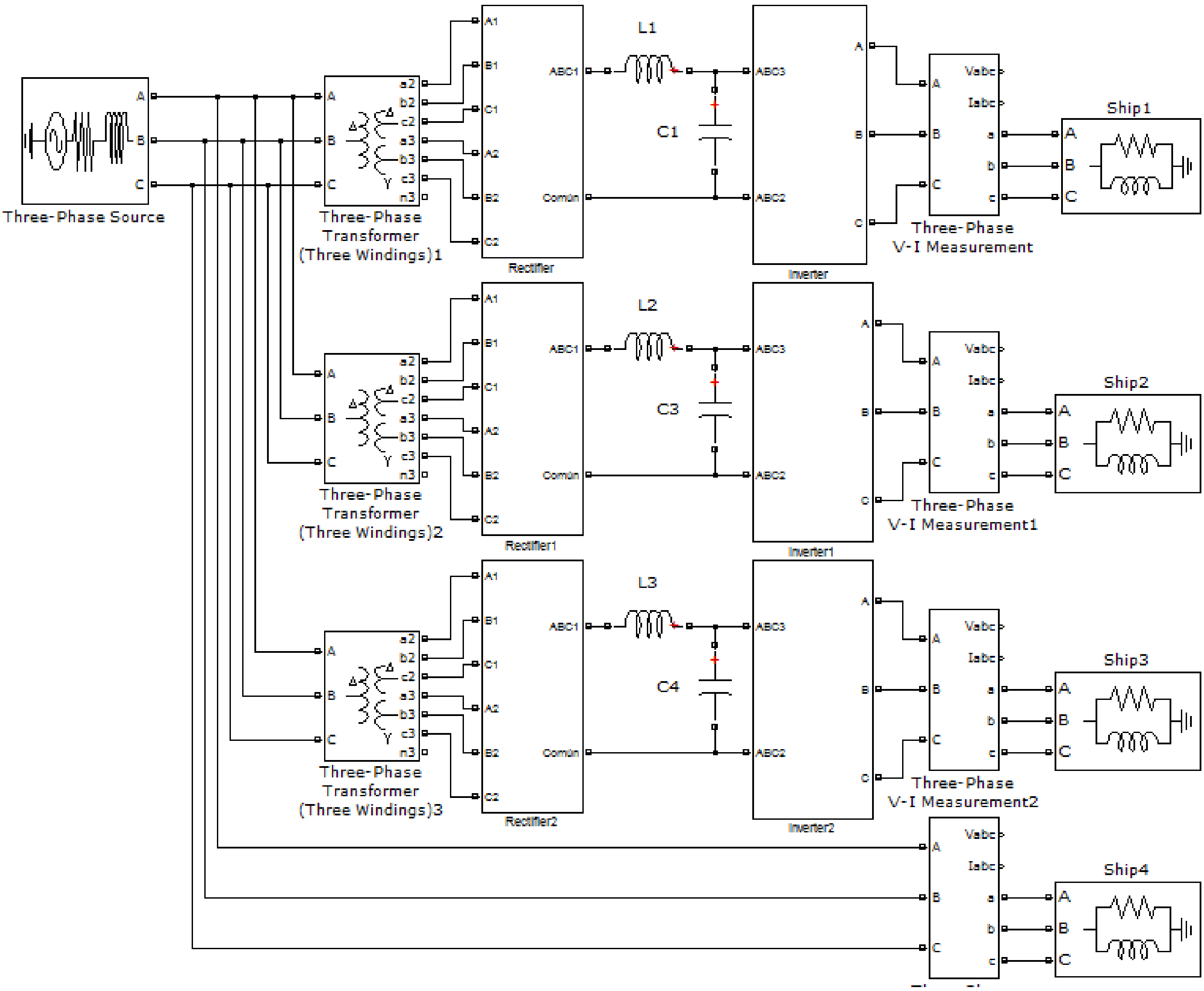

Figure 68: General HVSC system

This is the definitive version of the HVSC for four ships, ready to start with the simulations. Also, it must be remembered that in the reality, the electric feeders of the system would have an impedance of a certain value, which would mean a loss of energy through the circuit. However, in order to simplify the simulations, the value of these impedances has been considered zero.

7. Simulation and analysis

Once the designed system is finished, it is time to start running the simulations and to see how the current, voltage and frequency change under different conditions. Different trials will be done, simulating problems and variable conditions. Later, the results of these trials will be analyzed and compared to the regular ones in normal conditions.

7.1. Normal conditions

Before start testing the system in situations that could cause problems, it is necessary to have a reference, so the results obtained after the tests can be compared to something. This reference will be the system working under normal conditions.

Also, doing the simulation of the system without taking into account issues or programmed changes in the loads allows adjusting correctly the parameters of elements of the circuit such as resistances, inductances and capacitances. This adjustment is important to fulfill the quality requirements of the results. For example, the inductance and the capacitance of the DC link must have the right values to obtain a steady DC signal; or the inductances of the inverter will have to be correctly adjusted so they can convert the PWM signal created by the IGBTs into sine waves.

The time of the simulation is generally of 2 seconds, but the images will be cut shortly after 1 second, because at this time the flow is already stabilized and it allows watching more clearly the figures. In the cases where the figures are the same in different systems, except for the range of values, it will be shown the image corresponding to the system of electric feeder 1 as example. The results in normal conditions are the following:

- Voltage and current generated by the source. This is the same energy that reaches directly the fourth ship, and it can be seen how the voltage of each phase oscillates between 8,500 and -8,500 V, while the Vrms is of 6,000. Regarding to the current, each phase reaches a value between 1,200 and 1,400 A, and the RMS value is of 960 Arms.

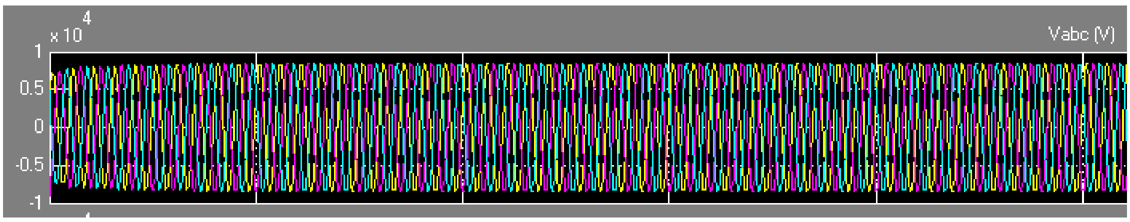

Figure 69: Voltages of the source / in electric feeder 4 (1)

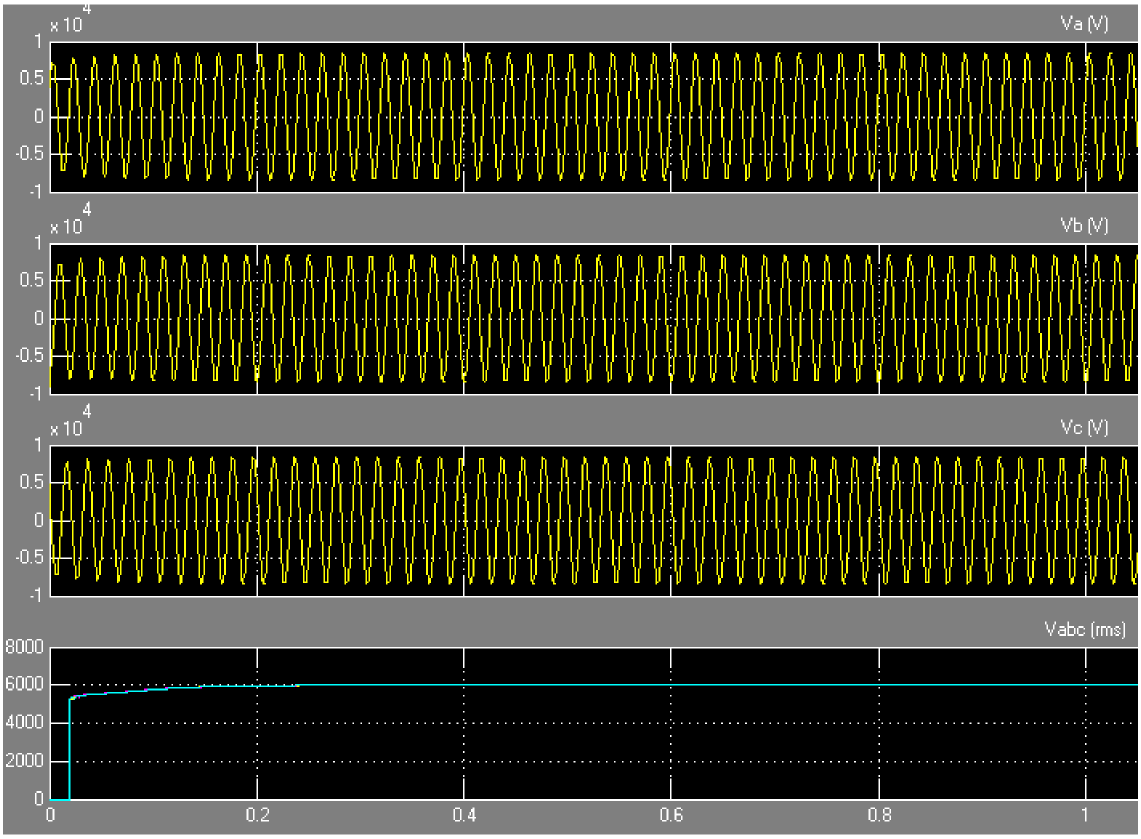

Figure 70: Voltages of the source / in electric feeder 4 (2)

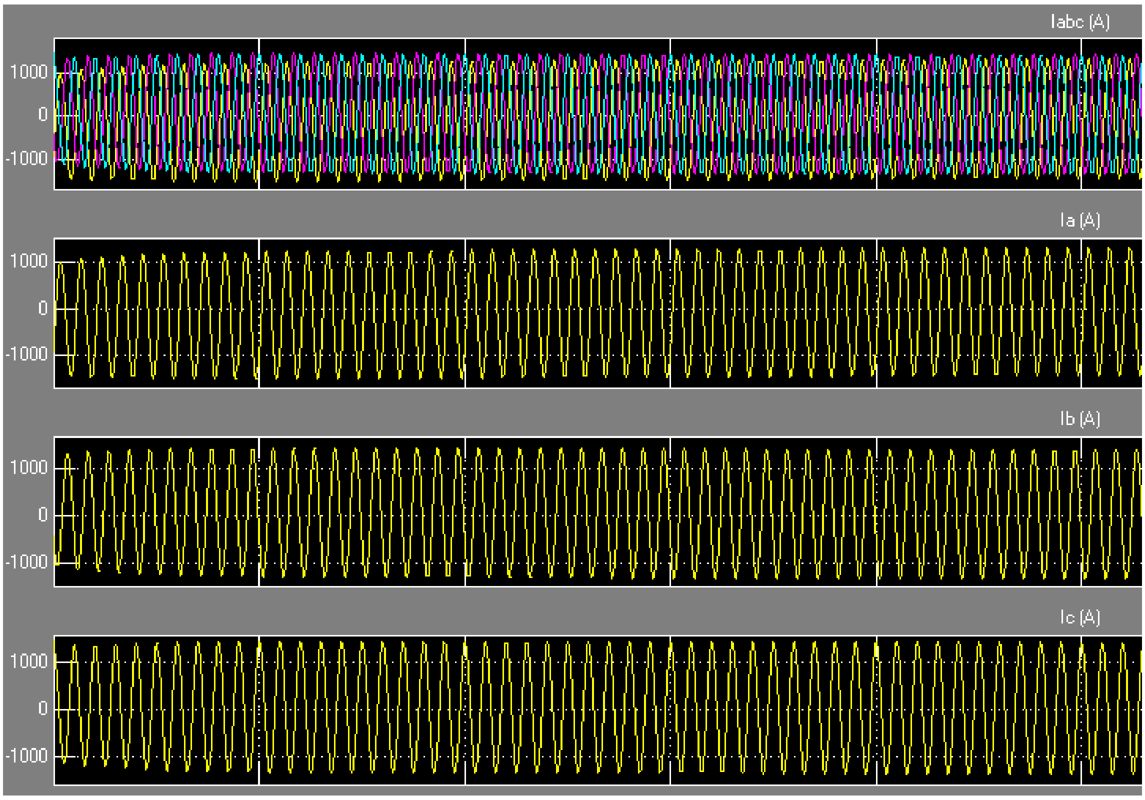

Figure 71: Currents of the source / in electric feeder 4 (1)

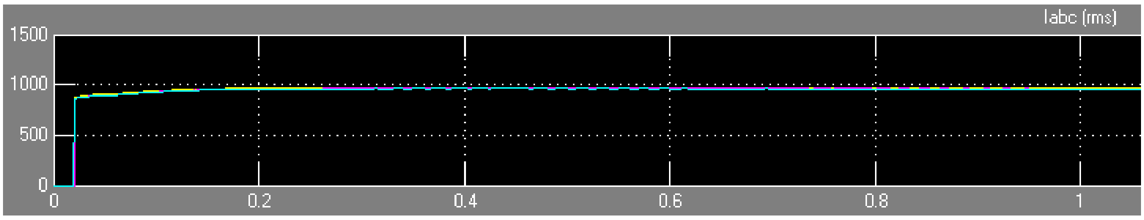

Figure 72: Currents of the source / in electric feeder 4 (2)

- Voltage after the inductance and the capacitance of the DC link. Here the electricity is in DC form, and it has different voltage in each one of the ships' subsystems, although the shape of the current remains the same.
  - In the subsystem of electric feeder 1, after it is stabilized it oscillates between 12,850 and 12,950 V.
  - In subsystem 2, oscillates between 13,920 and 14,020 V.
  - In subsystem 3, the oscillation is between 14,770 and 14,840 V.

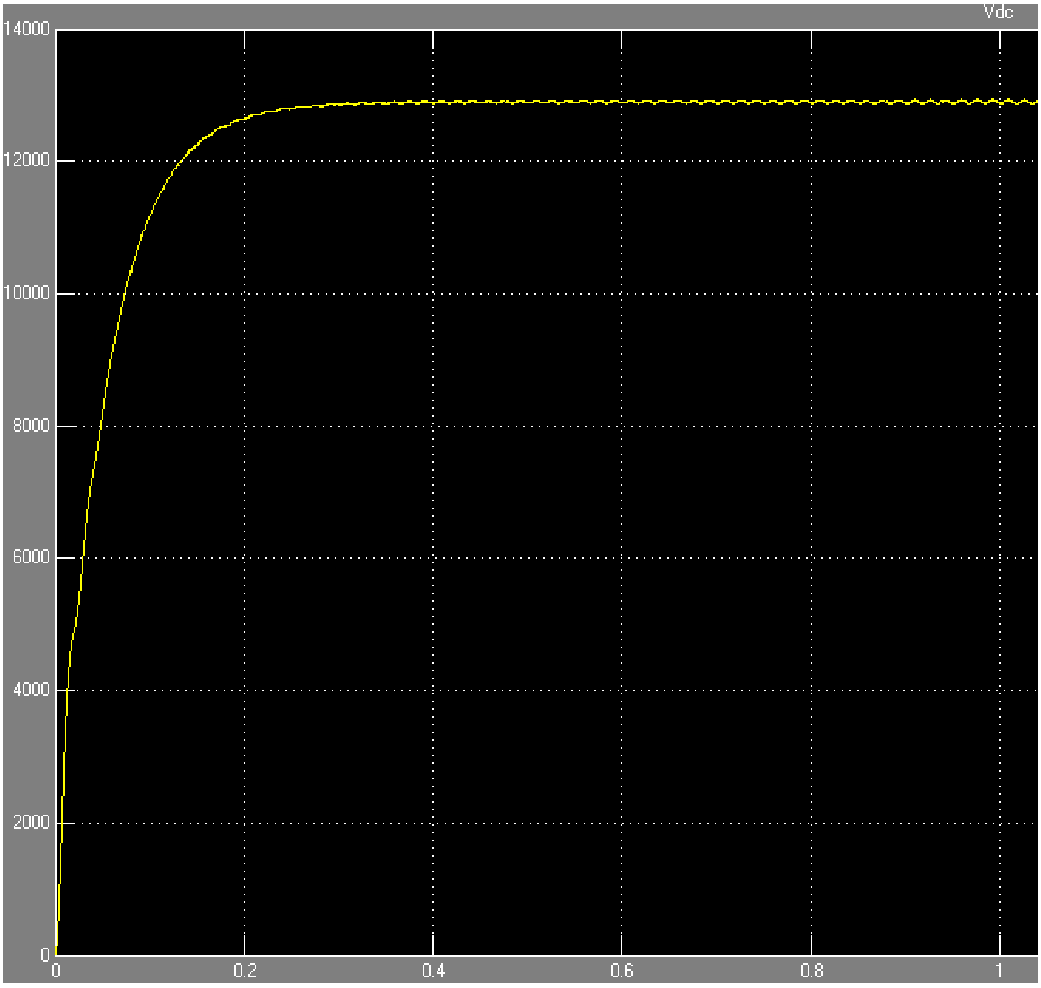

Figure 73: Voltage in DC link of subsystem 1

- Voltage and current after the inverter. Here the voltage values remain the same for all three subsystems, although this does not happen with the currents. In each phase, the Vrms is stabilized at a value of approximately 6,600. Regarding the currents, they change in the following pattern:

- In subsystem of ship 1, the RMS current stabilizes around 440 Arms.
- In subsystem 2, the RMS current is of 700 Arms.
- Subsystem of ship 3 has an RMS current of around 880 Arms.

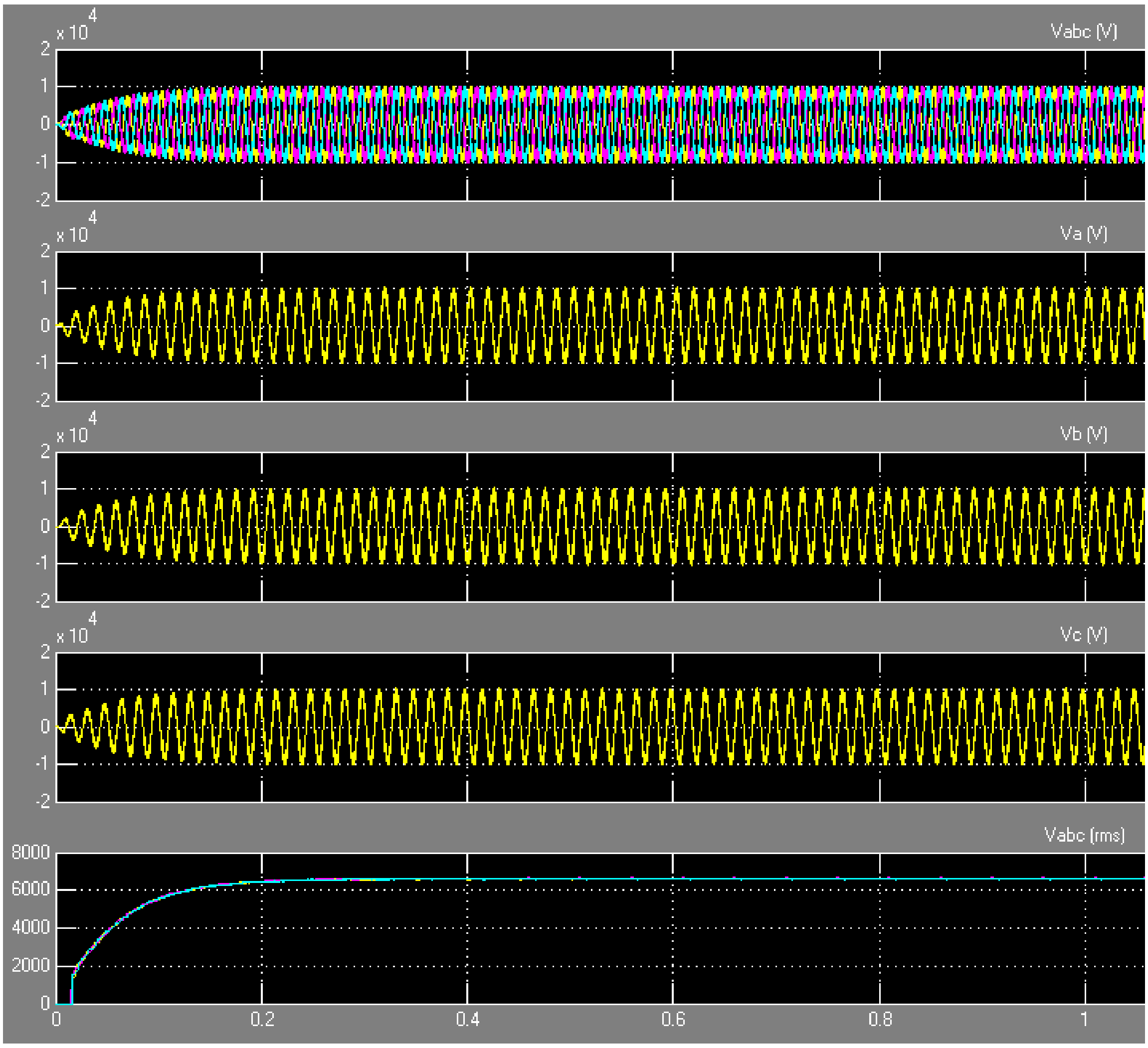

Figure 74: Voltages after the inverter in electric feeder 1

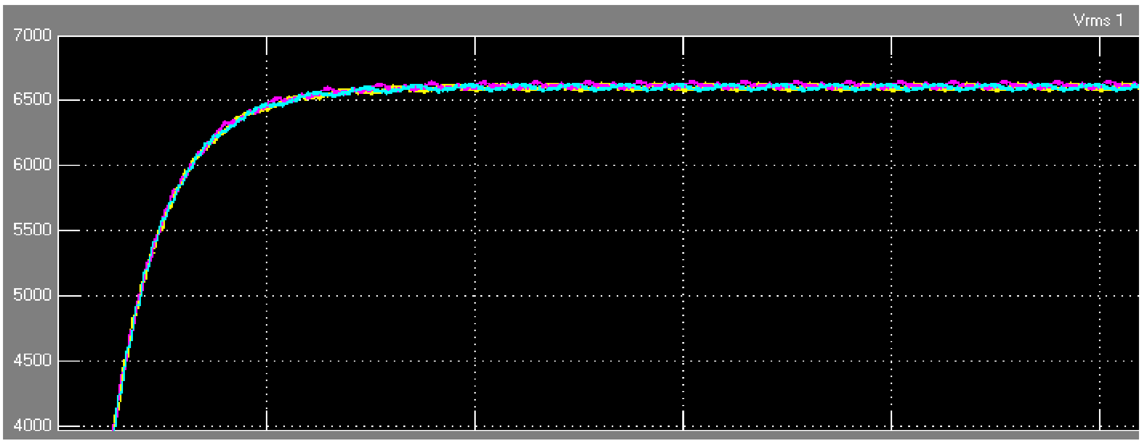

Figure 75: Detail of Vrms in electric feeder 1

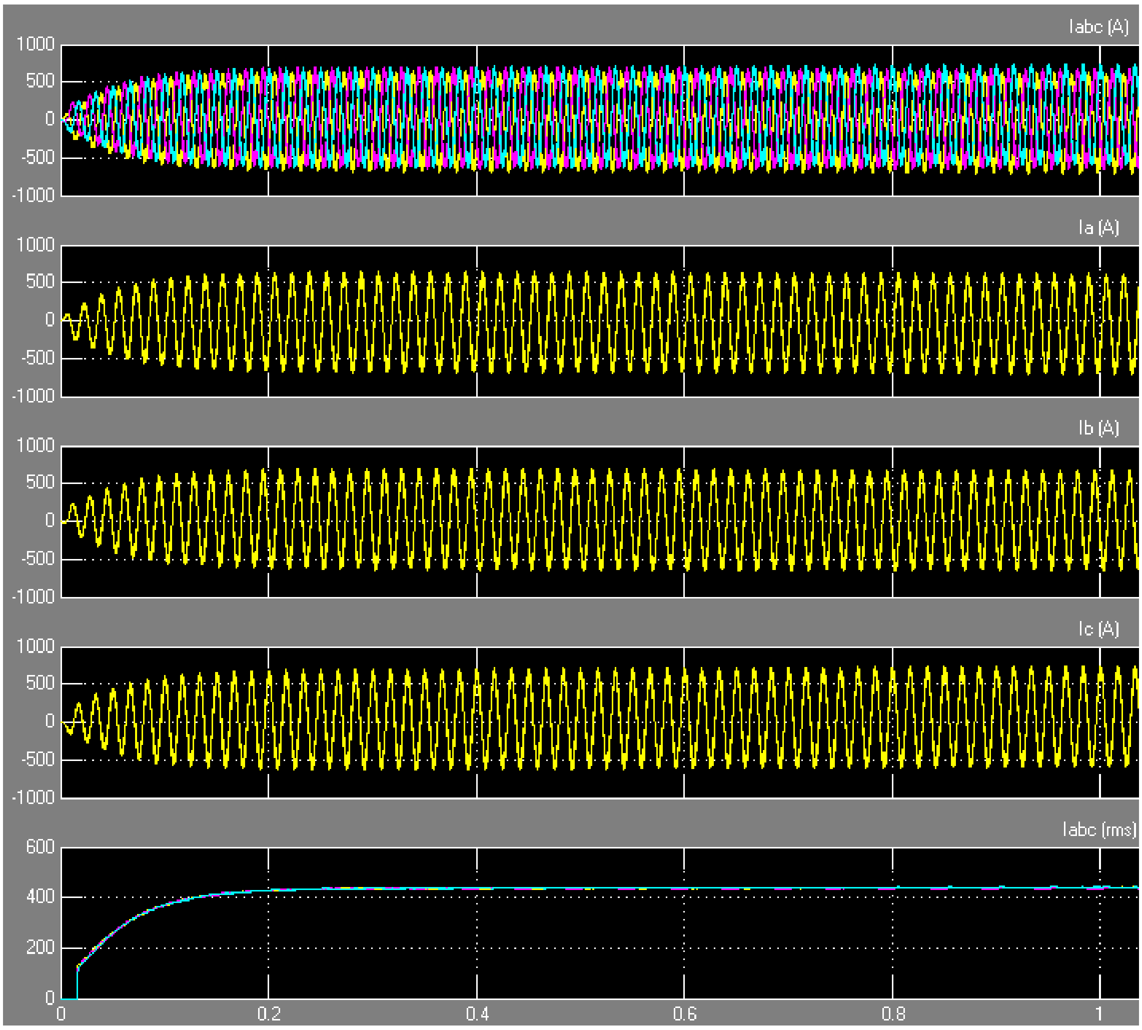

Figure 76: Currents after the inverter in electric feeder 1

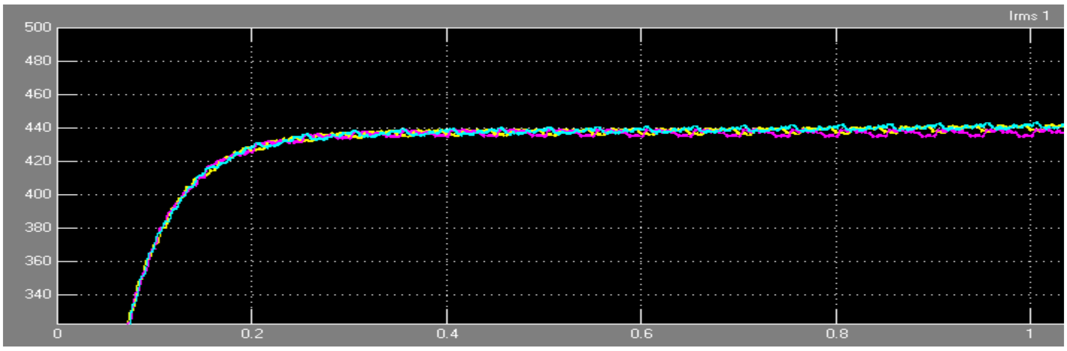

Figure 77: Detail of Arms in electric feeder 1

7.2. Short circuit in electric feeder 1

After having seen the performance of the system in steady conditions, it is time to start testing it with a programmed short circuit. This short circuit will take place in the electric feeder 1, between the inverter and the ship, which would represent a failure of the cable joining the ship and the pier. It is programmed that the short circuit will have a duration of 0.25 seconds (between seconds 0.75 and 1), after which the connection shall be reestablished.

The results of the simulations are the following:

In electric feeder 1:

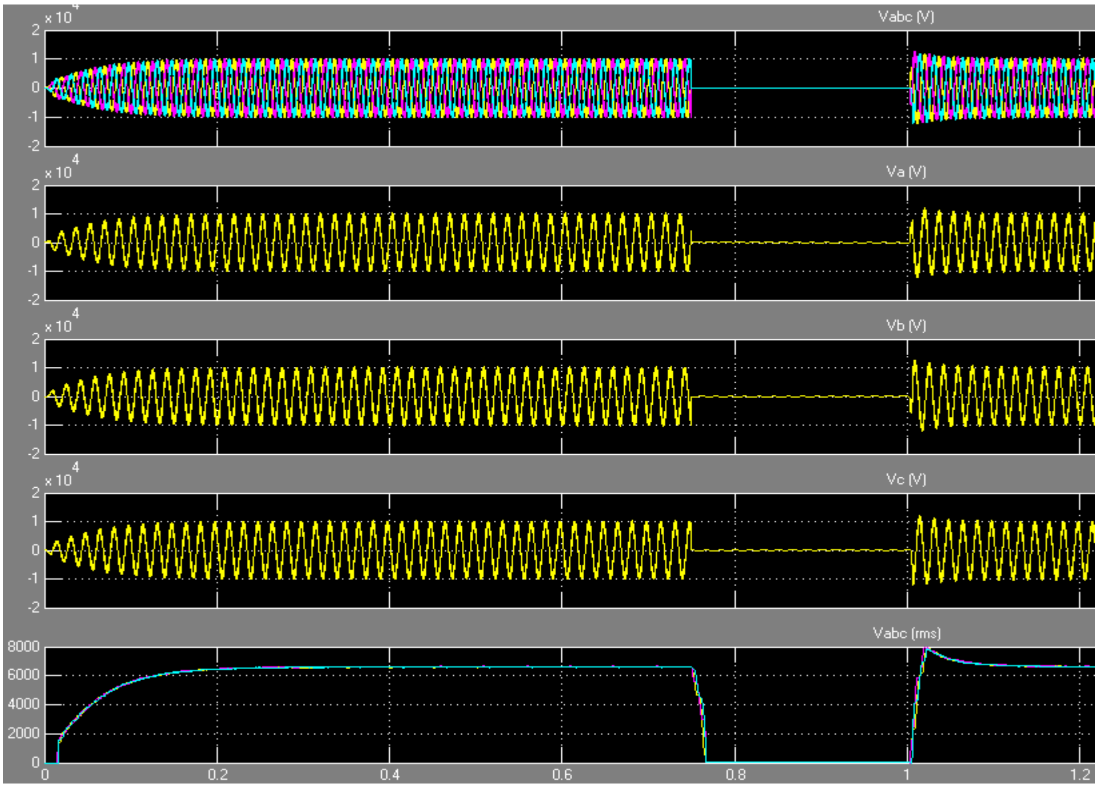

Figure 78: Voltages in electric feeder 1 with SC in electric feeder 1

The voltages in the electric feeder where the short circuit is produced fall to zero abruptly, and when the connection is established again, it reaches a high peak of approximately 8,000 Vrms. After that, the voltage returns to the previous conditions and is stabilized around 6,600 Vrms.

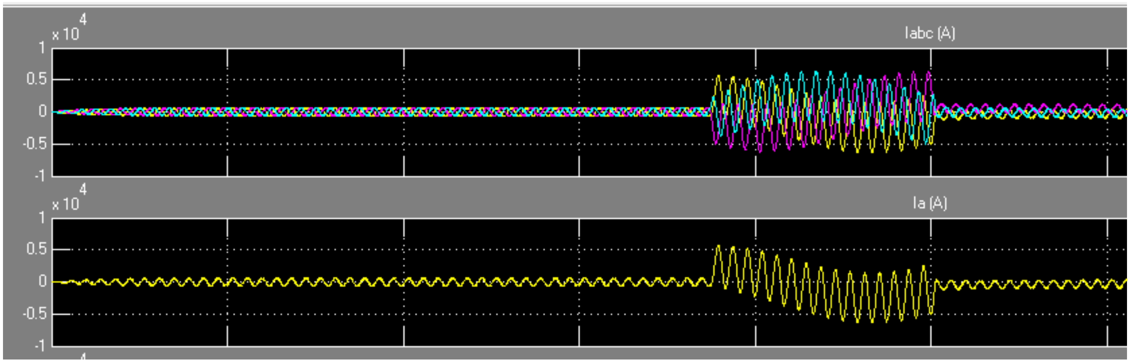

Figure 79: Currents in electric feeder 1 with SC in electric feeder 1 (1)

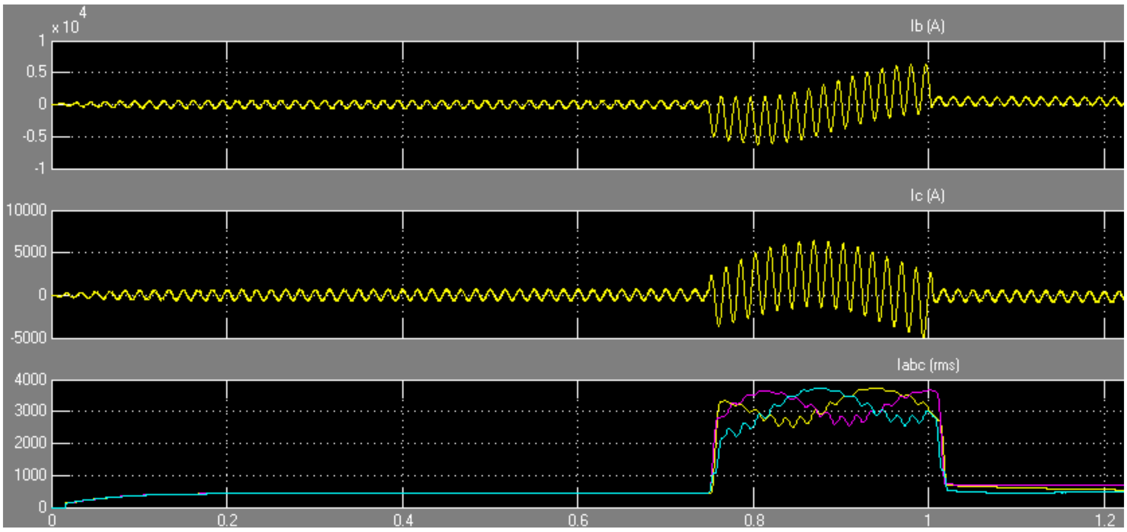

Figure 80: Currents in electric feeder 1 with SC in electric feeder 1 (2)

Regarding the currents, when the short circuit is produced in the electric feeder each phase reaches peaks of over ±5,000 A, which is huge compared to the regular oscillations between approximately ±600 A. Also the RMS current increases abruptly, as it goes up to values of around 3,700 Arms, eight times higher than the 440 Arms in normal conditions.

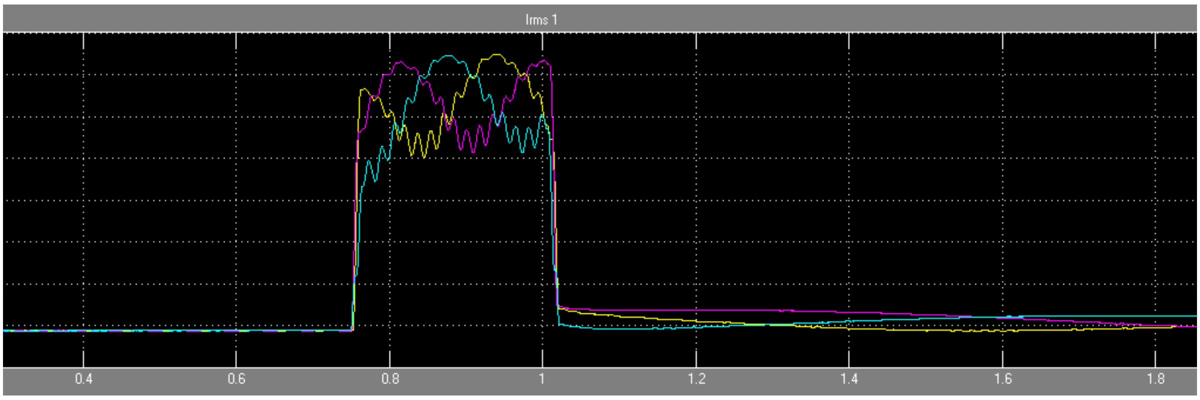

Figure 81: Detail of Arms in electric feeder 1 with SC in electric feeder 1

It can be noticed that after the short circuit has finished and the normal conditions have been reestablished, the current does not return to be as stable as it was previously. Otherwise, it fluctuates in a range of 420 to 620 Arms, big enough to be observed.

In electric feeder 2 and 3:

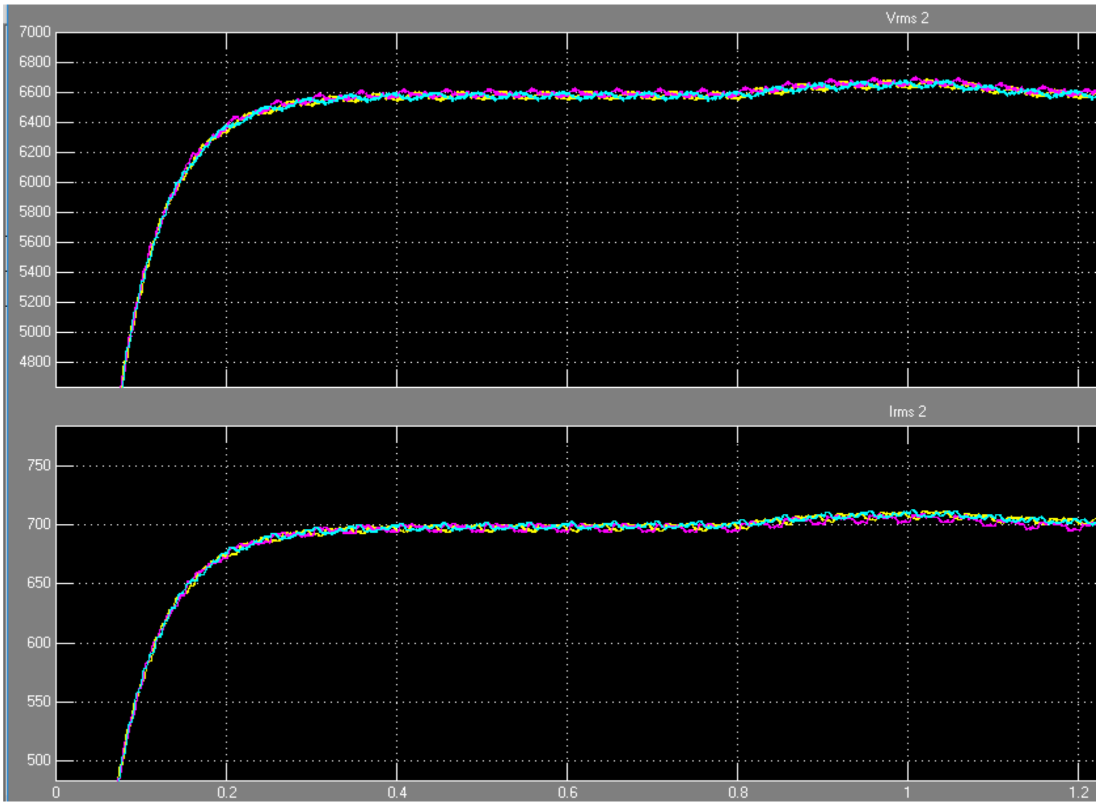

Figure 82: Vrms and Arms in electric feeder 2 with SC in electric feeder 1

In electric feeders 2 and 3, the effect of the short circuit happening in electric feeder 1 is barely noticeable, specially looking at the currents. Figure 82 shows the results in feeder 2, which are similar to the ones appearing in electric feeder 3, except for the values. The alterations produced are:

- In electric feeder 2, RMS voltage reaches 6,700 Vrms and then goes back to 6,600. RMS current goes up to 710 Arms and returns to 700 when short circuit is finished.
- In electric feeder 3, RMS voltage escalates to 6,730 Vrms before going back to 6,600. The current reaches approximately 890 Arms and then is again of 880.

In electric feeder 4:

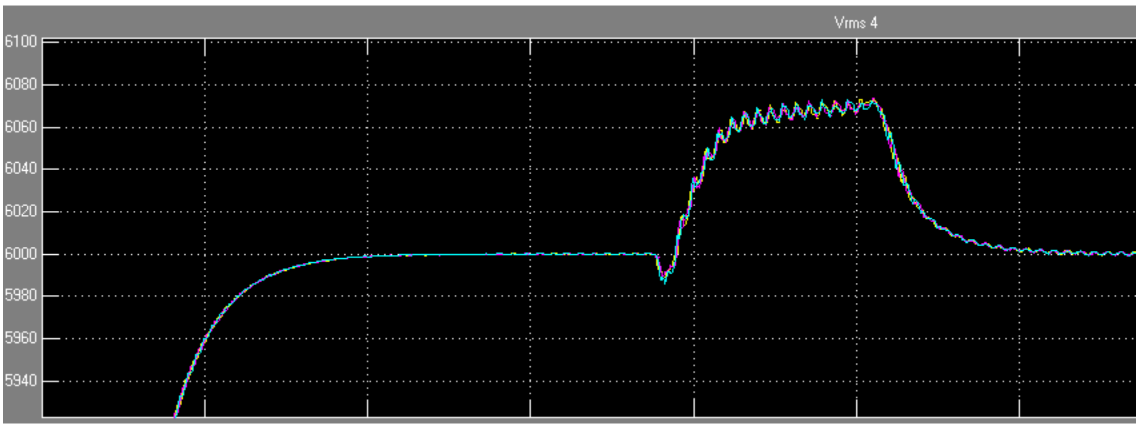

Figure 83: Vrms in electric feeder 4 with SC in electric feeder 1

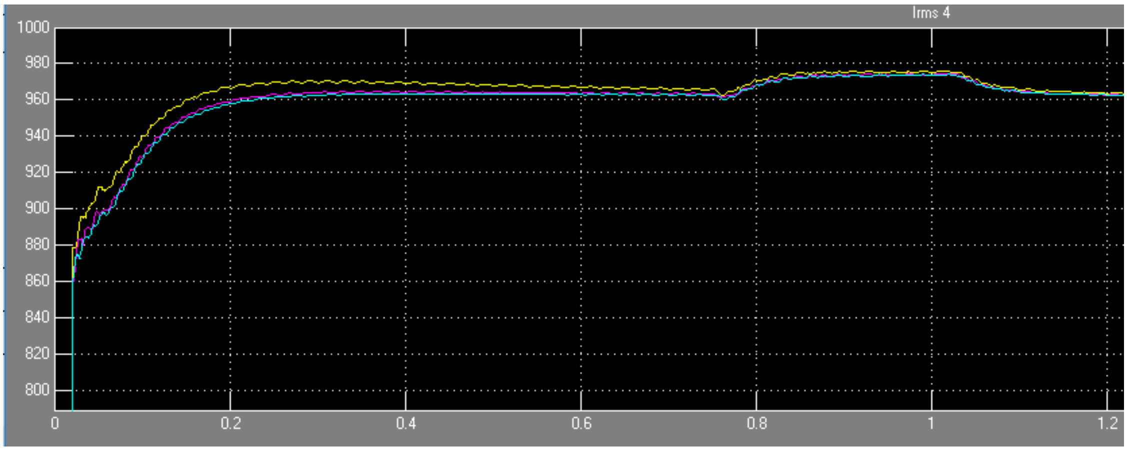

Figure 84: Arms in electric feeder 4 with SC in electric feeder 1

Like in feeders 2 and 3, in the electric feeder connecting the source with ship 4 the alterations are small, but they still exist. During the short circuit, RMS voltage in electric feeder 4 reaches a value of 6,070 and then it goes back fast to the regular 6,000 Vrms, which is an increase even smaller than the ones happening in electric feeders 2 and 3. Concerning the current, it rises to 975 Arms, returning to 960 once the short circuit is over.

The reason these big perturbations happening in electric feeder 1 affect in such a small percentage to the rest of feeders is found in the elements in the inverter of the electric feeder 1. Specifically, in the inductances of the inverter, who are acting to regulate these alterations that are reaching the inverter from the load's side.

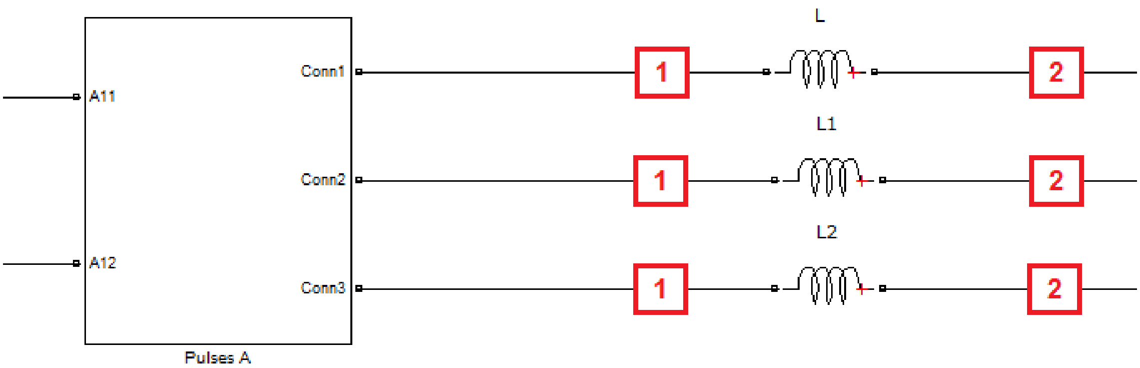

Figure 85: Points of voltage measurement in the invertir of electric feeder 1

Voltage has been measured in the points indicated in Figure 85, which is representing the inverter of electric feeder 1.

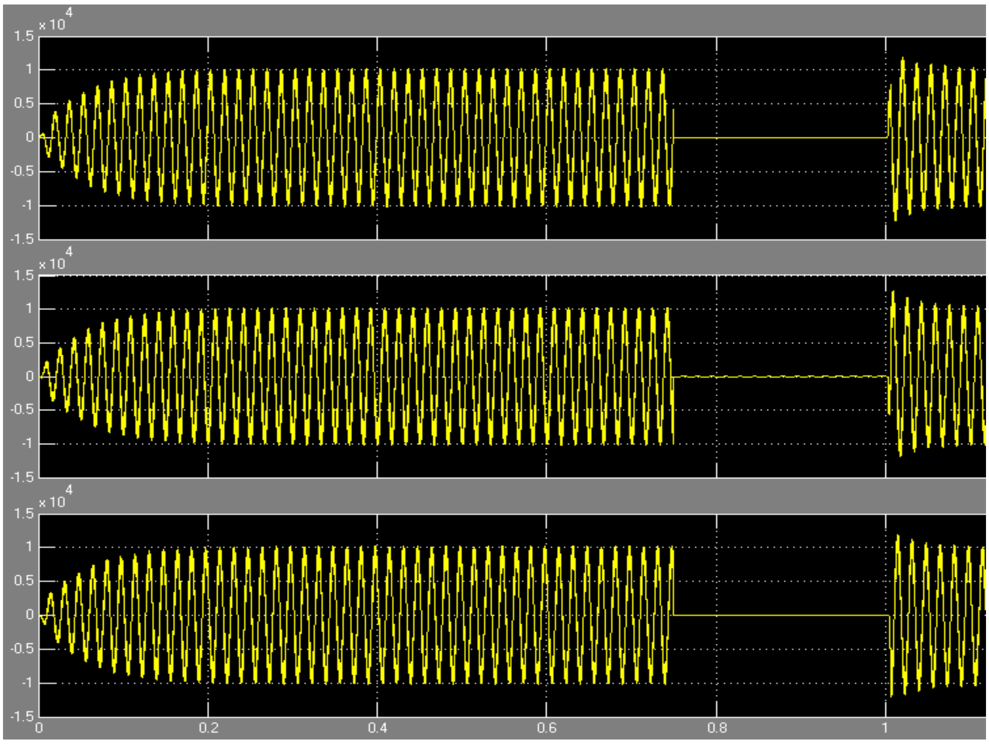

Figure 86: Voltage measurements in point 2

As Figure 86 shows, the voltage in point 2 still has the perturbations that the short circuit causes. But after it goes through the inductances and reaches point 1, it has changed to what can be seen in Figure 87:

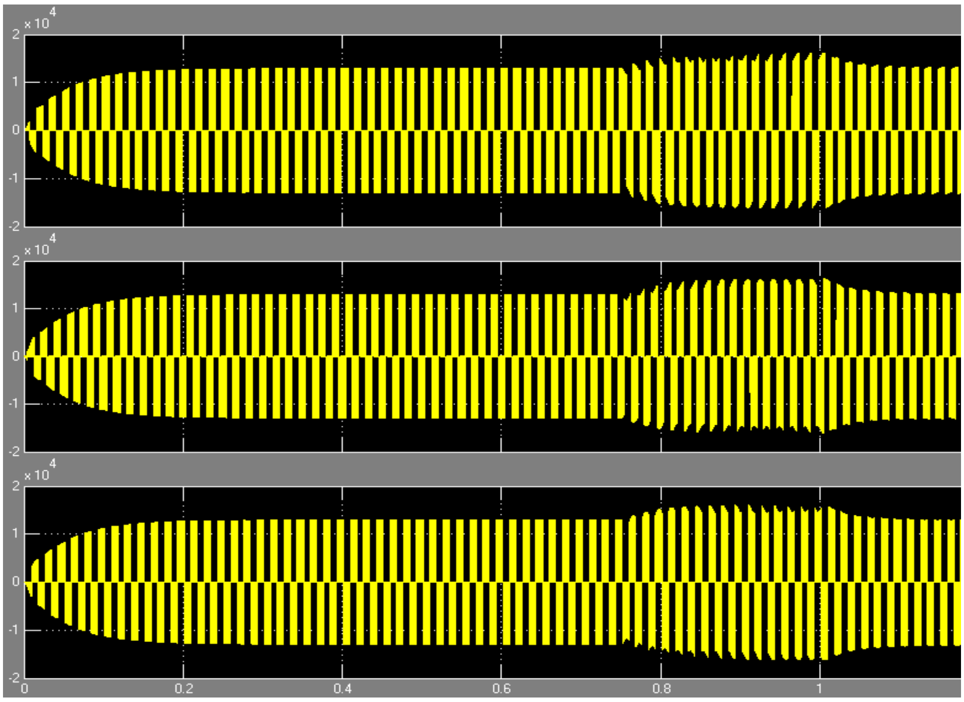

Figure 87: Voltage measurements in point 1

Thanks to these inductances, the energy has now a more stable value, and although it still causes variations in the rest of the electric feeders, they are much less relevant than if there wasn't any element acting as a barrier.

Finally, it must be noted that no frequency alterations have been observed, either in the electric feeder where the short circuit is produced or in others.

7.3. Short circuit in electric feeders 2 and 3

Short circuits happening in electric feeders 2 and 3 will have similar effects in the rest of the system to the ones caused by the fault in electric feeder 1. In fact, the resulting figures have the same shapes that the ones shown previously, except for the values reached during the short circuit. As loads 2 and 3 are bigger than load 1 (8 and 10 MVA against the 5 MVA of load 1), the effects of short circuits affecting these ships are going to be slightly bigger than the ones appearing in the section above.

7.3.1. Results of short circuit in electric feeder 2

With a short circuit happening between 0.75 and 1 second, the following changes are observed.

In electric feeder 2, where the short circuit is produced:

- RMS voltage reaches a peak of 8,700 Vrms at the end of the short circuit, and then it is stabilized back to 6,600.
- RMS current has oscillations between 3,000 and 4,200 Arms as long as the short circuit lasts, and then it goes back to oscillate around 700, although it is not as stable as previously, just like what happened with the short circuit in electric feeder 1.

In electric feeders 1 and 3:

- In electric feeder 1, RMS voltage goes from 6,600 to approximately 6,800 Vrms during the short circuit, while the current grows from 440 to 450 Arms.
- In electric feeder 3, RMS voltage reaches a value of 6,800 Vrms, and the RMS current increases from 880 to 900 Arms.

In electric feeder 4:

- Voltage goes from 6,000 to 6,150 Vrms, and current from 960 to 985 Arms.

7.3.2. Results of short circuit in electric feeder 3

When the same short circuit is produced in electric feeder 3, the results are as exposed:

In electric feeder 3:

- RMS voltage has a peak of 9,500 Vrms at the end of the short circuit.
- The oscillations of the current during the short circuit are approximately between 3,200 and 4,700 Arms.

In electric feeders 1 and 2:

- In electric feeder 1, voltage reaches almost a value of 6,900 Vrms, while the current grows to near 460 Arms.
- In electric feeder 2, voltage goes up to approximately 6,850 Vrms and current increases to 720 Arms.

In electric feeder 4:

- Here the voltage surpasses the 6,200 Vrms during short circuit, while the current escalates to almost 1,000 Arms.

7.4. Short circuit in electric feeder 4

The programmed short circuit taking place in the feeder 4 of the system is the same tested in the previous feeders, but this one requires special attention, as it is happening in the electric feeder that is connected directly to the source without intermediate elements. That is why the effects caused by this short circuit in the other electric feeders is expected to be bigger than the before tested.

The results of the simulations in different electric feeders are as follows.

In electric feeder 4, electric feeder of the short circuit:

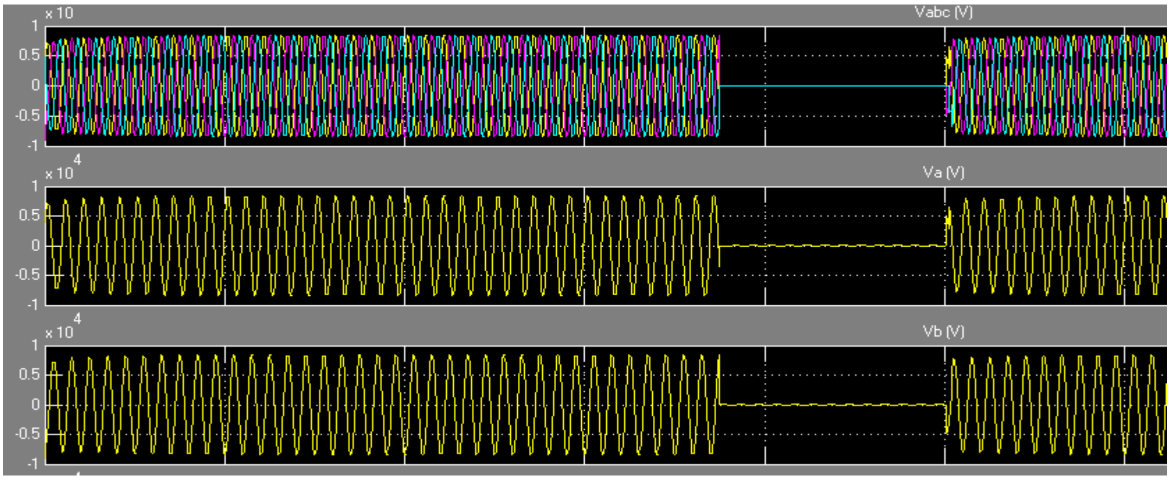

Figure 88: Voltages in electric feeder 4 with SC in electric feeder 4 (1)

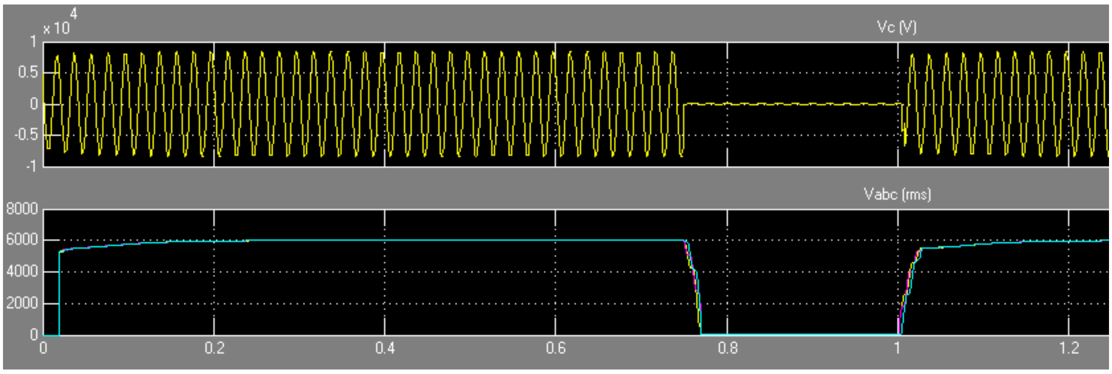

Figure 89: Voltages in electric feeder 4 with SC in electric feeder 4 (2)

The effects the short circuit in electric feeder 4 has in the feeder 4 itself are similar to the ones that have short circuits in electric feeders 1, 2 and 3 in themselves. The main difference appreciated is that in this case, there is not a voltage peak when the short circuit ends, but the RMS voltage grows slowly from zero until it reaches again 6,000 Vrms.

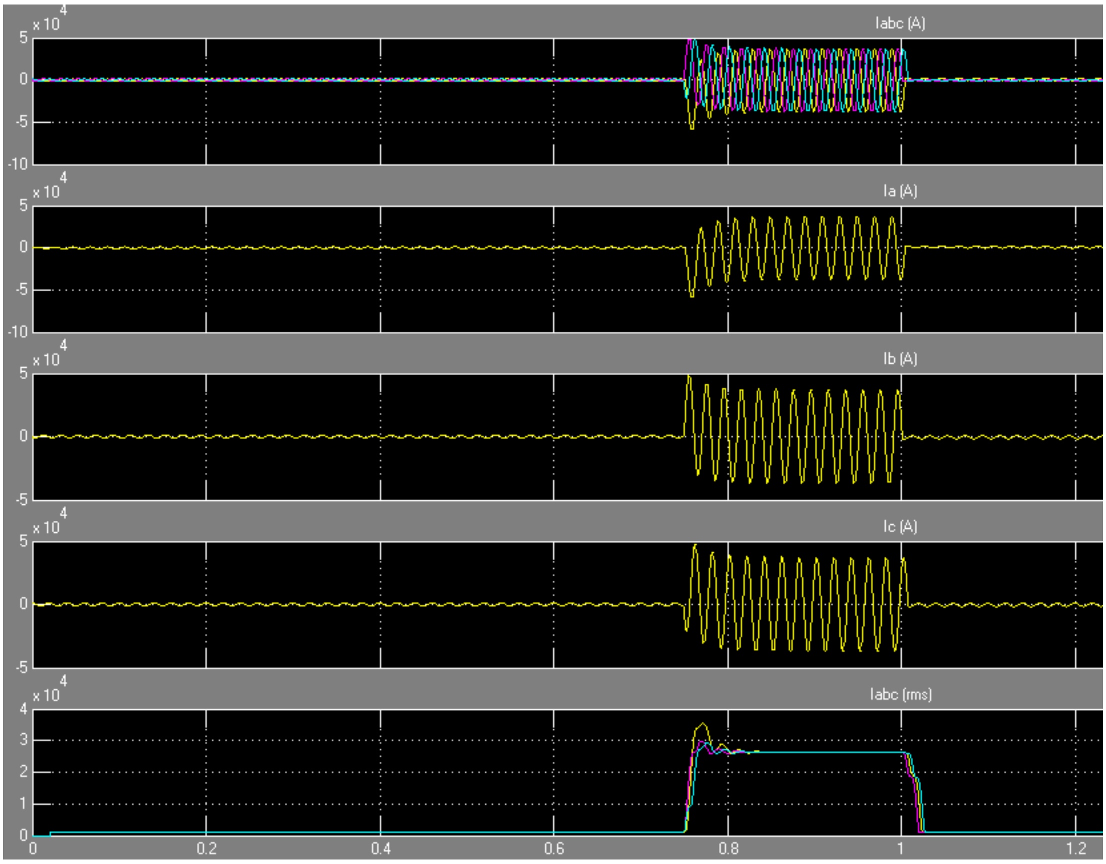

Figure 90: Currents in electric feeder 4 with SC in electric feeder 4

The biggest effect caused by the short circuit in this electric feeder can be seen in the currents. While the RMS values during the short circuits in the other cases reached as a maximum 4,700 Arms, in the case of this electric feeder it has a current peak of over 35,000 Arms at the beginning of the failure, stabilizing around 26,000 Arms during the rest of the time that the short circuit lasts.

In electric feeder 1:

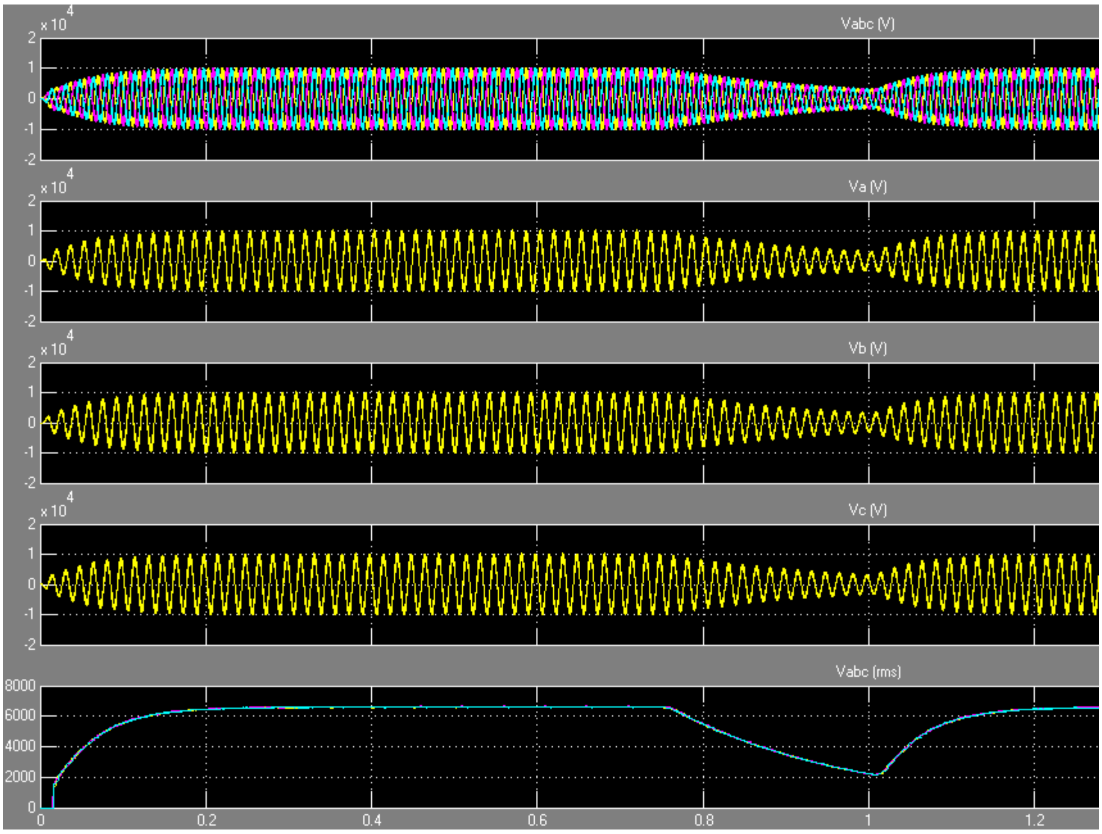

Figure 91: Voltages in electric feeder 1 with SC in electric feeder 4

In this electric feeder, the voltage starts to decrease when the short circuit starts, and when the failure is over it begins to grow again, until it reaches its previous 6,600 Vrms. If the short circuit lasted longer, the voltage would continue to go down until reaching a value of zero. But in this case, as the short circuit has a duration of 0.25 seconds, the voltage reaches a minimum peak of 2,200 Vrms before starting to grow.

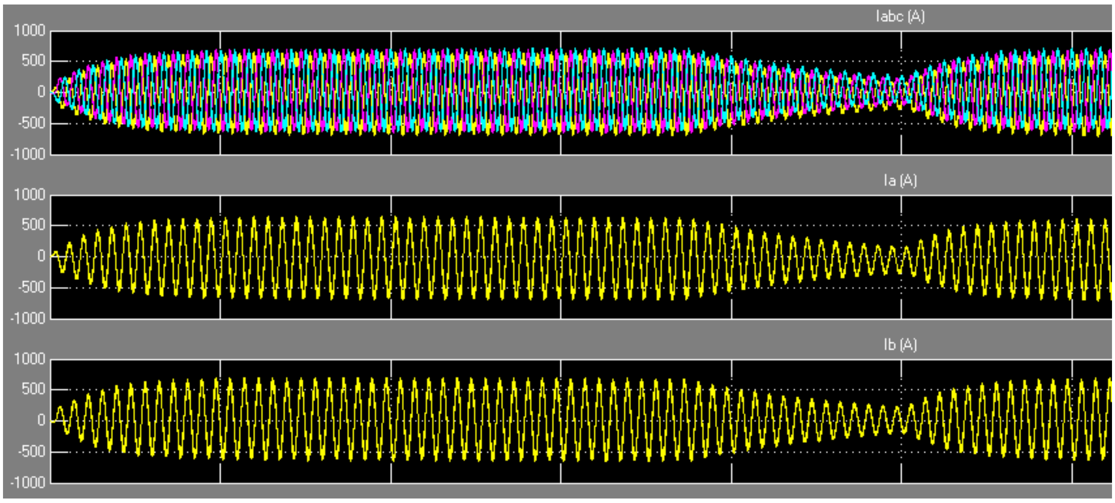

Figure 92: Currents in electric feeder 1 with SC in electric feeder 4 (1)

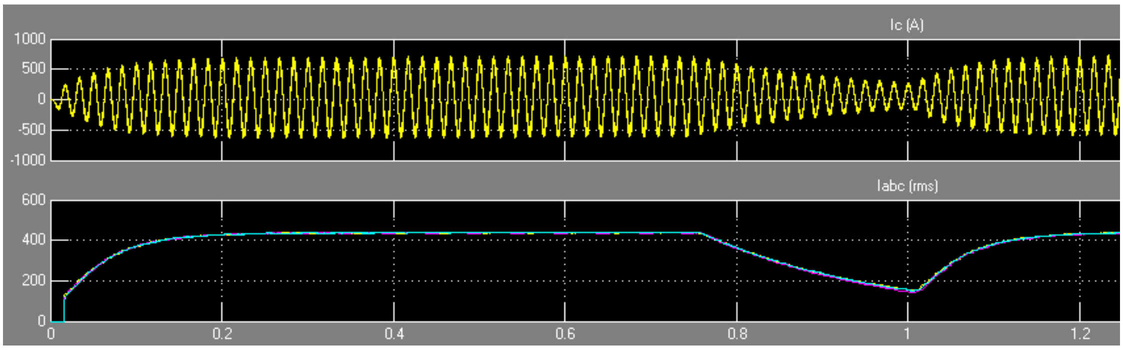

Figure 93: Currents in electric feeder 1 with SC in electric feeder 4 (2)

With the currents there is a similar result to the obtained with the voltages, as the current starts to decrease gradually when the short circuit appears and goes back to its previous value when the short circuit is finished. With this short circuit lasting 0.25 seconds, the minimum peak reached by the RMS current is of 150.

In electric feeders 2 and 3:

In these two feeders, the effects are similar to the ones that appear in electric feeder 1, as only the values of the peaks change. It must be remembered that the peaks' values depend on how much does the short circuit last, and in this case the results are:

- In electric feeder 2, the minimum RMS voltage is of 1,500 Vrms and the RMS current of 150 Arms.
- In electric feeder 3, the peak of the RMS voltage is of 1,250 Vrms, and in the current case is of 150 Arms.

As it may be noticed, the minimum voltage peak reached during the short circuit changes from one electric feeder to other, unlike what is happening with the current values: these remain in all three cases very near to 150 Arms.

With the short circuit happening in this electric feeder, also no changes in frequencies have been observed.

Also, some tests have been done with short circuits lasting more time, to observe if the effects caused are different. Specifically, a short circuit of 0.6 seconds (from second 0.8 to 1.4) has been tested in all the electric feeders, but the consequences have been the same in practically all cases. Only with the short circuit tested in electric feeder 4 some changes have been seen: as the more the short circuit lasts, the more the voltage and current of other electric feeders decrease, so the drop of these values has been higher. In electric feeder 1, the voltage's fall has been of a 93%, reaching a 98% in electric feeder 3.

7.5. Load changes in electric feeder 1

When talking about ships at berth, load changes might be quite big. This is the reason why this test and the following are going to be performed adding or subtracting a load of 1 MVA, with the same PF of 0.8 that the loads representing the ships have.

In the trials, the extra load will be connected or disconnected to the electric feeder depending of the situation tested, but the change will be done always at the same moment; at 0.75 seconds.

7.5.1. Load increase in electric feeder 1

For this test, the just mentioned load of 1 MVA will be added to the already existent load of 5 MVA of the ship, starting at 0.75 seconds and during the rest of the simulation.

The results are the ones observed in the next figures.

In electric feeder 1:

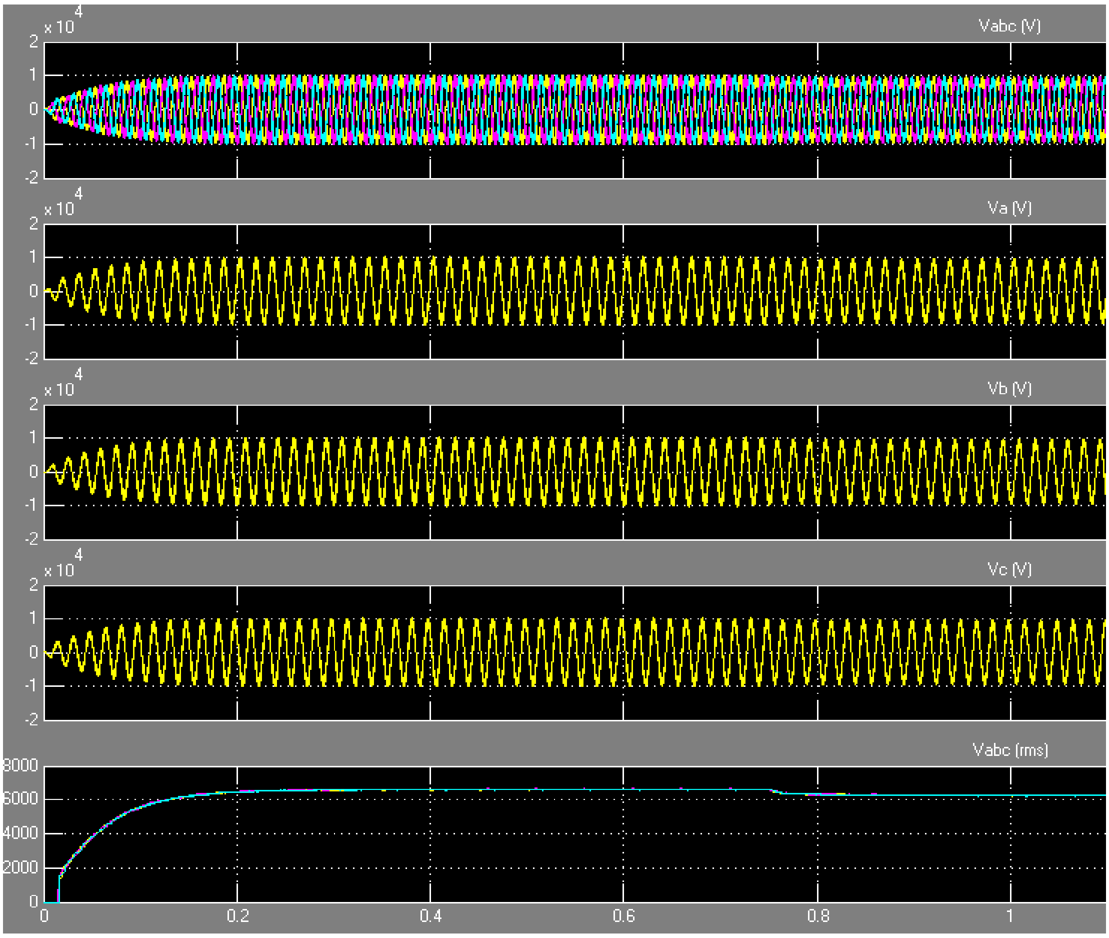

Figure 94: Voltages in electric feeder 1 with load increase in electric feeder 1

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Regarding the resulting voltages after the load increase, it can be seen at a first look that this increase means a subtle decrease of the RMS voltage, as it goes down from the stablished 6,600 to approximately 6,280 Vrms, stabilizing at this value.

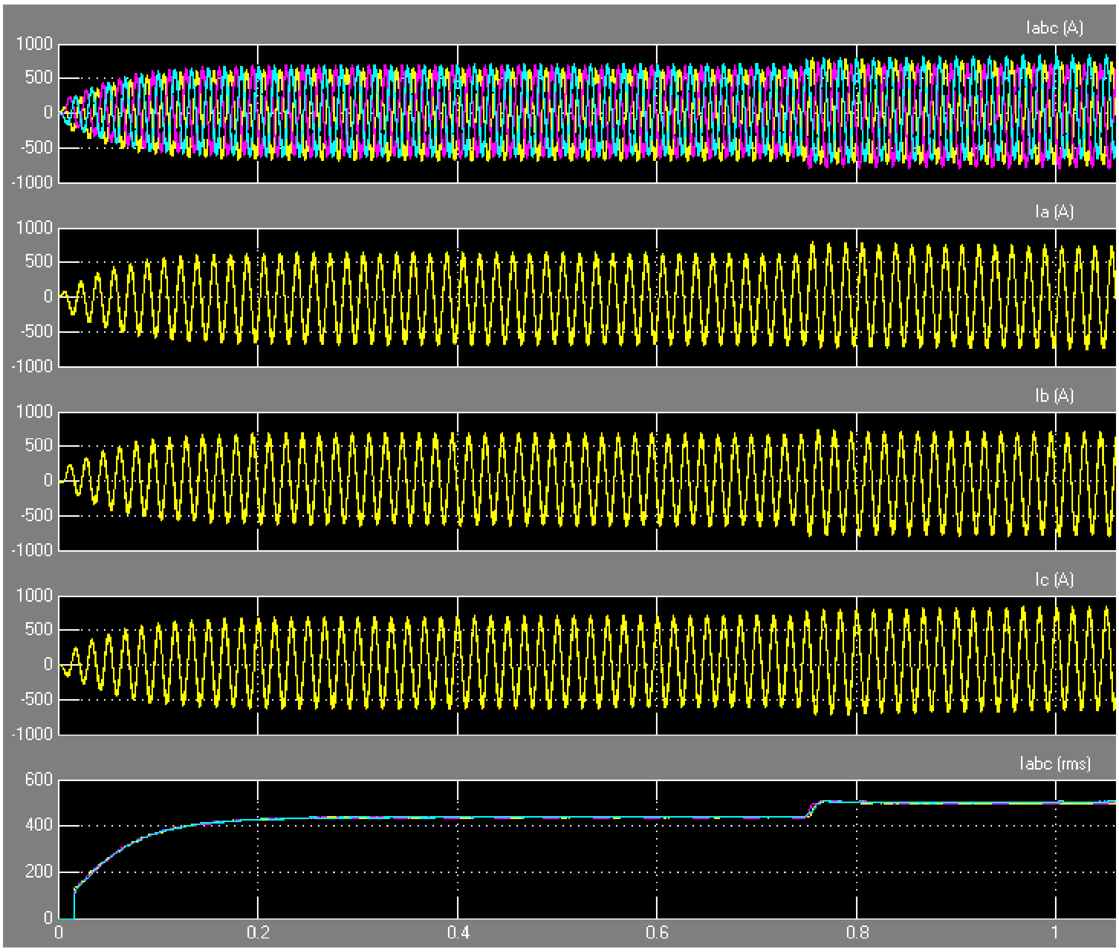

Figure 95: Currents in electric feeder 1 with load increase in electric feeder 1

The effects of the load increase are even easier to be observed in the currents results, as the increment of the current is obvious in every figure. Here the current grows, opposite to the voltage, and it goes up from 440 Arms to 500, where it is stabilized.

In electric feeders 2 and 3:

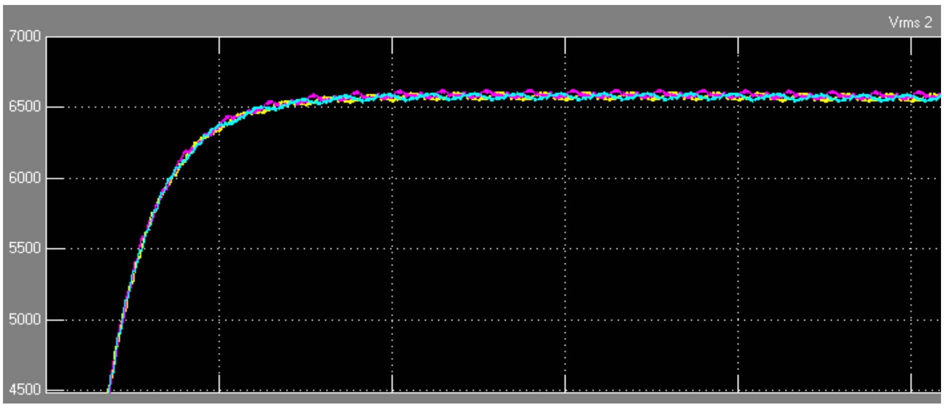

Figure 96: Vrms of electric feeder 2 with load increase in electric feeder 1

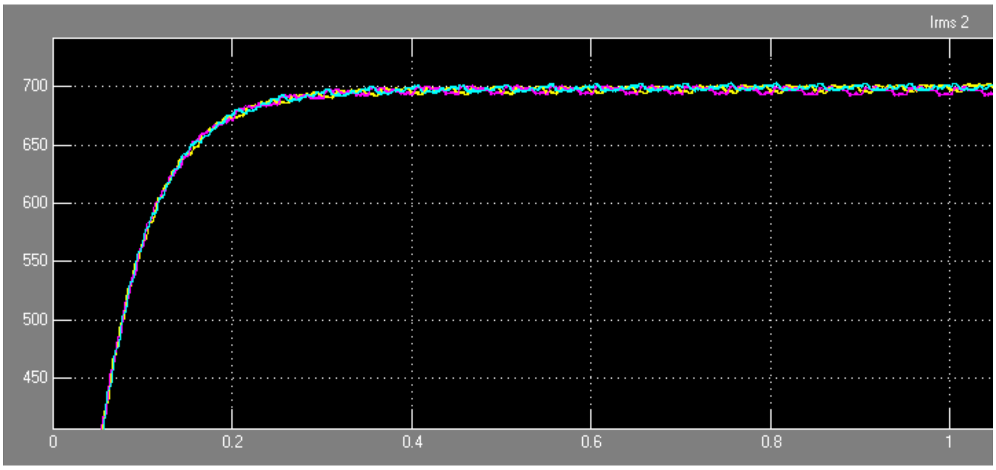

Figure 97: Arms of electric feeder 2 with load increase in electric feeder 1

As it can be seen in Figures 96 and 97, there are no side effects in feeder 2 of the load increase in electric feeder 1, as both RMS voltage and current remain unaltered. The same happens for electric feeder 3, where no effects are appreciated.

In electric feeder 4:

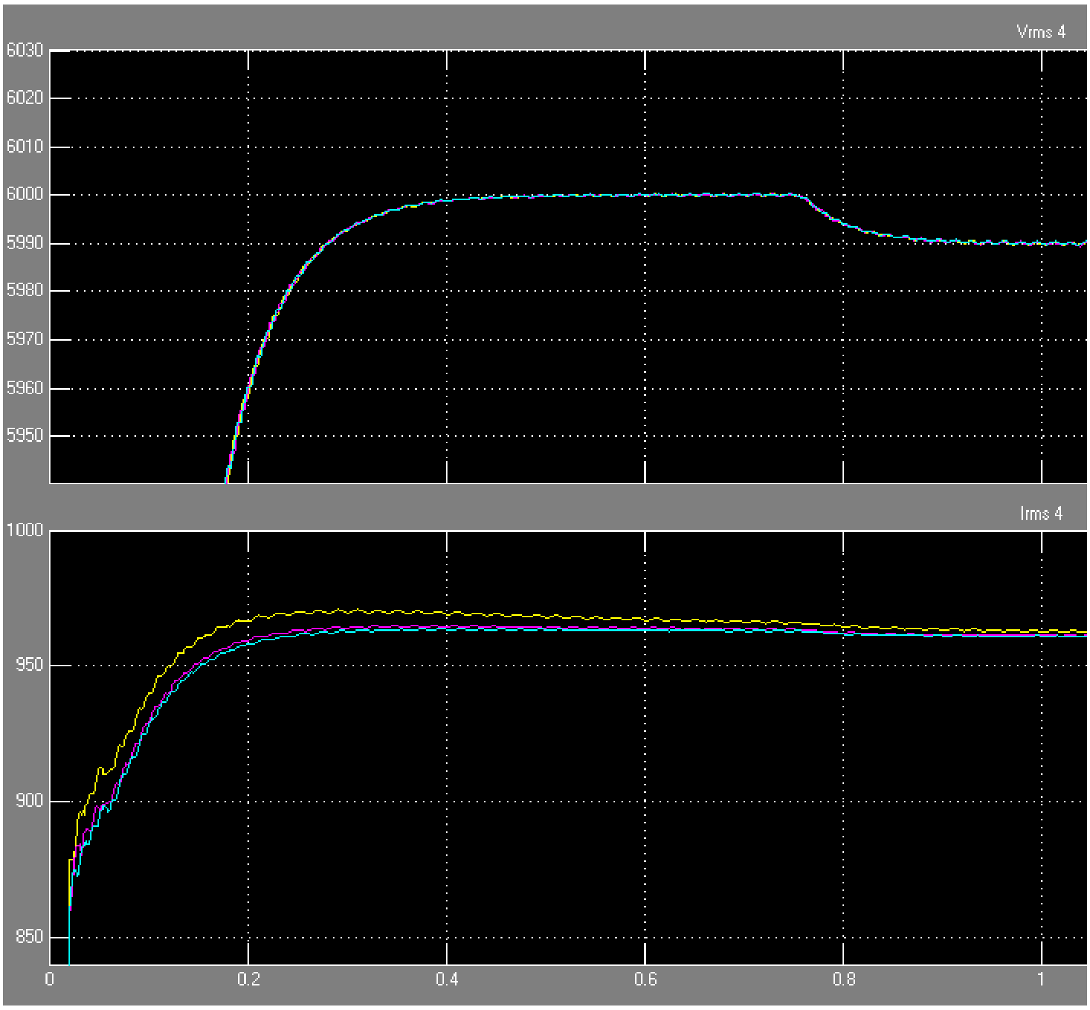

Figure 98: Vrms and Arms in electric feeder 4 with load increase in electric feeder 1

Figure 98 shows that there do exist effects of the load increase in electric feeder 1 that are reflected in electric feeder 4, although it is really subtle. In fact, RMS voltage only decreases about 10 Vrms, while the effects in the current can be neglected.

7.5.2. Load decrease in electric feeder 1

The load decrease test is similar to the load increase one, but in this case the load is going to be reduced from the initial 5 MVA to 4 MVA from second 0.75 and until the end of the test.

The results are as follows.

In electric feeder 1:

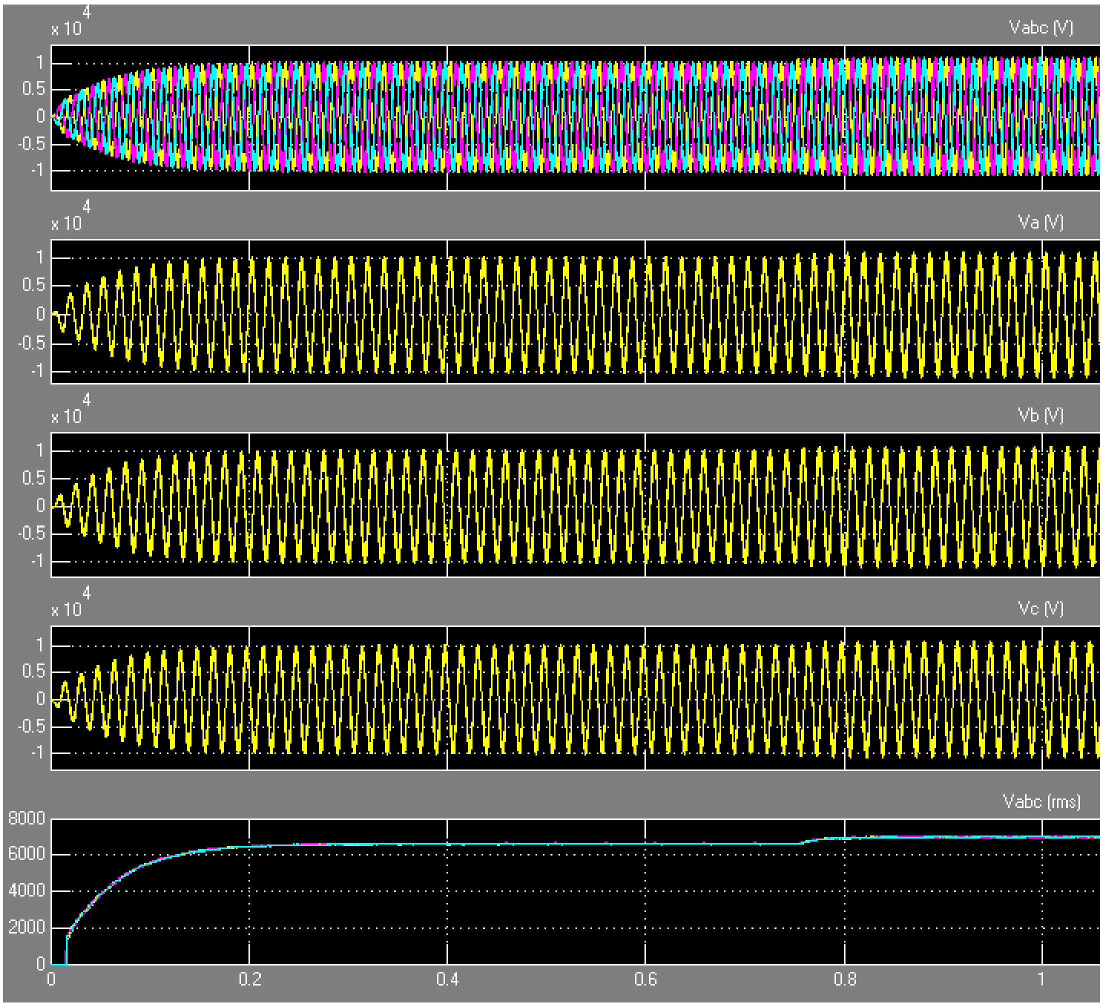

Figure 99: Voltages in electric feeder 1 with load decrease in electric feeder 1

The resulting voltages are similar to the ones obtained with the load increase test, but logically the RMS voltage augments instead of decreasing. The new voltage is stabilized at a value of 7,000 Vrms.

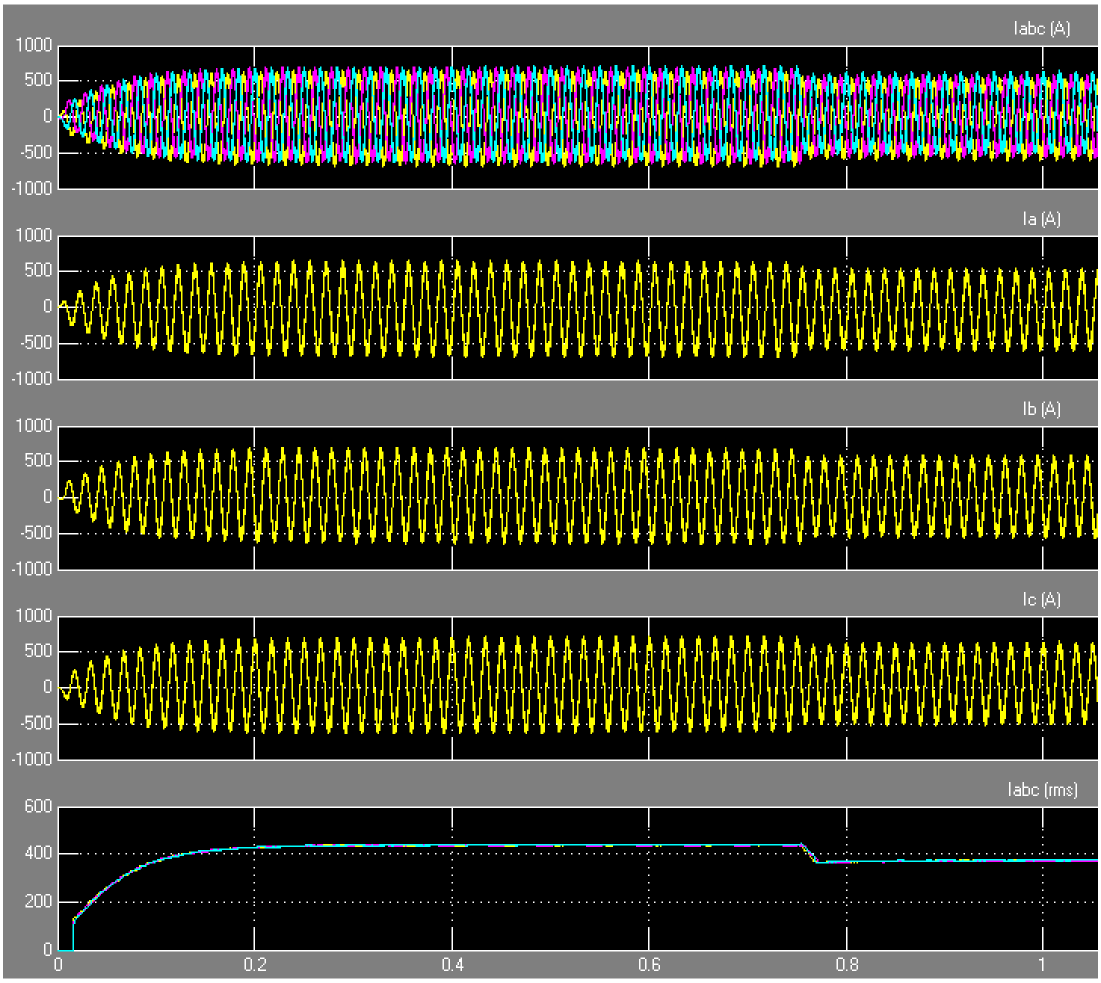

Figure 100: Currents in electric feeder 1 with load decrease in electric feeder 1

Like it was expected after seeing the precedents, the changes in the currents can also be observed at a first look. There is a decrease, opposed to the increase in the value, which goes from the RMS current of 440 Arms to the 370 where it is now stabilized.

In electric feeders 2 and 3:

As in the case of the load increase, there are no considerable effects observed in the voltage or the current of electric feeders 2 and 3.

In electric feeder 4:

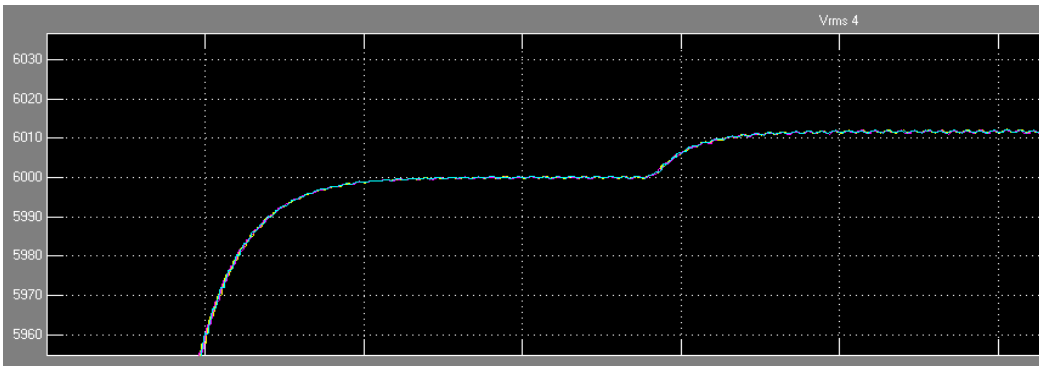

Figure 101: Vrms of electric feeder 4 with load decrease in electric feeder 1

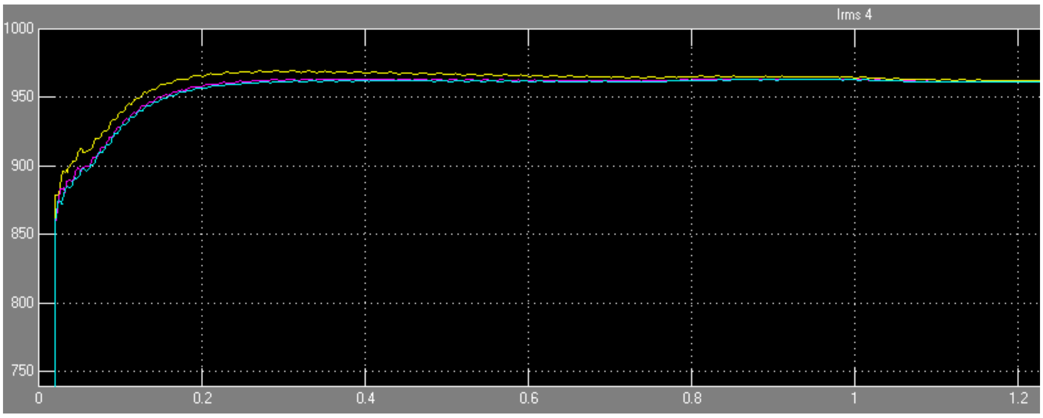

Figure 102: Arms of electric feeder 4 with load decrease in electric feeder 1

The effects of the load decrease in electric feeder 1 are small in feeder 4, but they are at least visible in the RMS voltage graphic, as it shows an increase of about 10 Vrms when the load change is produced. Meanwhile, on the current side the effects are practically neglected, as there is only a weak disturbance.

7.6. Load changes in electric feeders 2 and 3

In this section, the same change of load that was programmed in electric feeder 1 will be performed in electric feeders 2 and 3. From the initials 8 MVA and 10 MVA of each load, an increase or decrease of 1 MVA will be applied in second 0.75 and until the end of the simulation.

7.6.1. Load increase in electric feeders 2 and 3

The load increase of 1 MVA will be applied in the first test to the electric feeder 2, increasing it to a total of 9 MVA. After that, the same will be done in electric feeder 3, where the load will go from the initial 10 MVA to 11.

The results are similar to the ones obtained with the simulation done in feeder 1. The voltages and currents of the other two electric feeders with a converter system remain unaltered, but there are changes in the electric feeder where the load increased is produced, and small alterations in electric feeder 4. The values of these alterations are the following:

With the load increase in electric feeder 2:

- In electric feeder 2, voltage decreases from 6,600 to 6,300 Vrms, while current grows from 700 to 750 Arms.

- In electric feeder 4, RMS voltage decreases slightly to 5,990 Vrms, but there are practically no effects in the current.

With the load increase in electric feeder 3:

- In electric feeder 3, RMS voltage goes down to approximately 6,330 Vrms, and the current increases from 880 to 920 Arms.
- In electric feeder 4, the voltage decreases a little until it is around 5,992 Vrms. Again, effects in the current are neglected.

7.6.2. Load decrease in electric feeders 2 and 3

For the cases of load decrease, the same procedure explained above will be repeated. Load 2 will be reduced from 8 to 7 MVA starting at 0.75 seconds, and the respective load of ship 3 will go from 10 to 9 MVA.

Again results of these simulations are similar to the obtained in the test realized with electric feeder 1. There are no visible effects of the load decrease in the other two feeders with converter subsystems, but the electric feeder 4 and the feeder where the change of load is produced are affected. The effects of the load decreases are the following:

With the load decrease in electric feeder 2:

- In electric feeder 2, RMS voltage starts increasing with the load change, until reaching approximately 6,920 Vrms. By contrast, current decreases from 700 to 650 Arms.
- In electric feeder 4, the voltage grows up to 6,010 Vrms, but there are no noticeable changes in the current.

With the load decrease in electric feeder 3:

- In electric feeder 3, voltage increases and stabilizes at around 6,950 Vrms, while current goes down from 880 to 830 Arms.
- In electric feeder 4, RMS voltage rises slightly and is stabilized near 6,008 Vrms. Again there are no visible effects in the current of this electric feeder.

7.7. Load changes in electric feeder 4

The same load changes tested before will be done in electric feeder 4. After seeing the precedents, it is expected that voltage changes in this feeder will have a bigger effect in the other electric feeders than the previous cases, because it is affecting directly to the main supply feeder. However, the simulations must be carried to observe if the predictions are correct.

7.7.1. Load increase in electric feeder 4

The load increase of 1 MVA in electric feeder 4 at 0.75 seconds increments the load of the ship from 5 to 6 MVA. The results in the rest of the system are as follows.

In electric feeder 4, where the load increase happens:

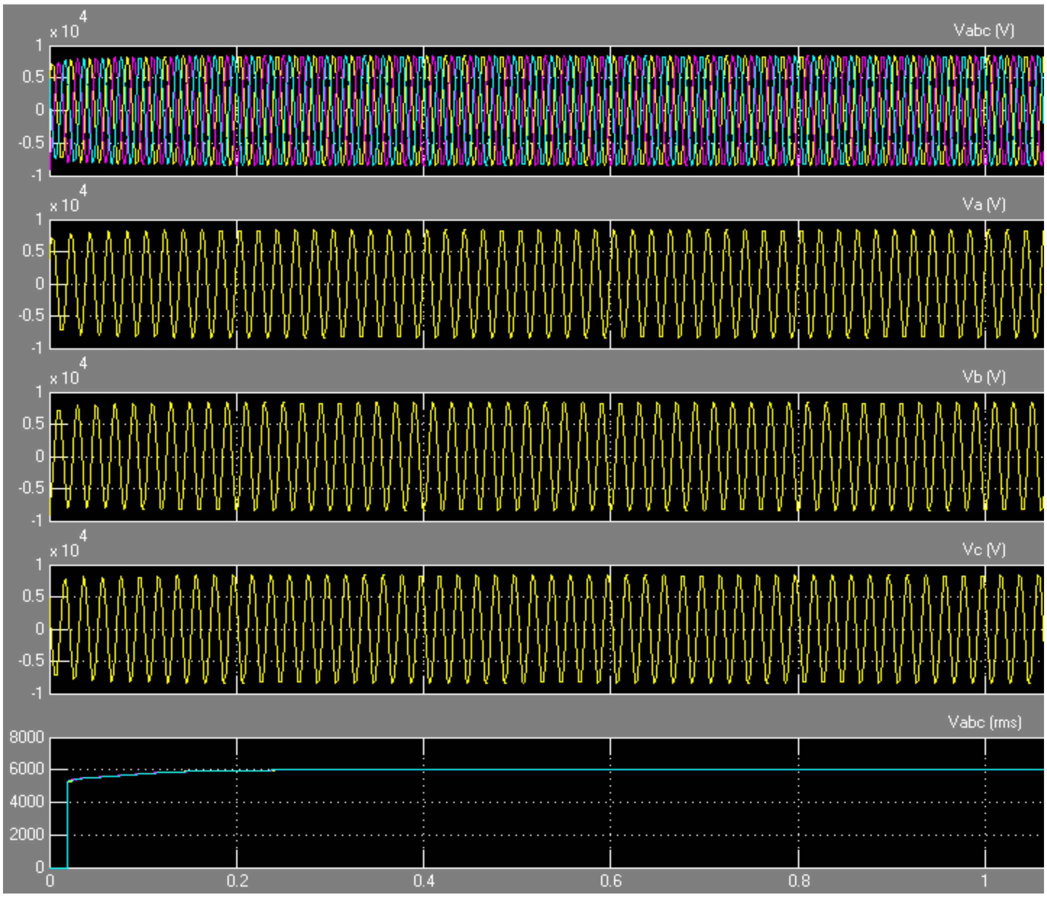

Figure 103: Voltages in electric feeder 4 with load increase in electric feeder 4

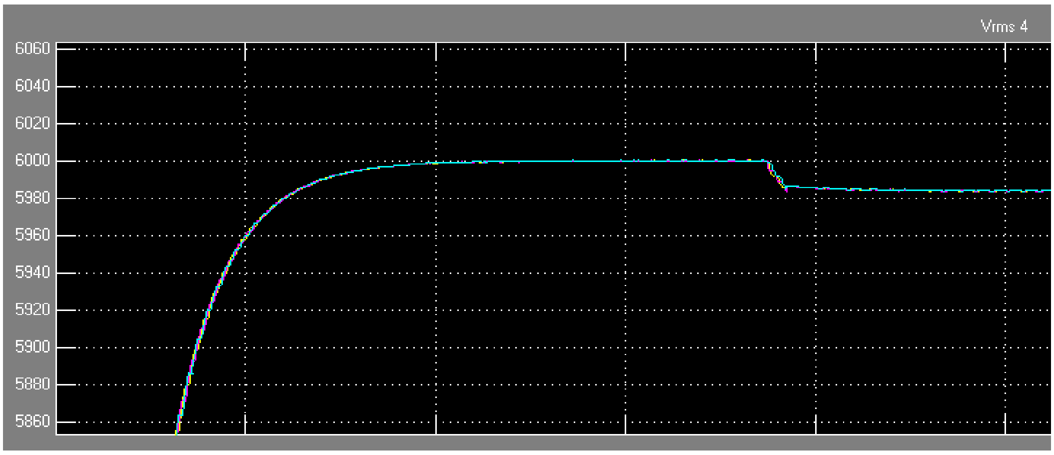

Figure 104: Detail of Vrms in electric feeder 4 with load increase in electric feeder 4

Regarding the voltages, what can be seen at a first look at the graphics is that the effect of the load increase is so small that it can't be noticed from that far. However, extending the image makes possible to observe that there do exist a change, although it is relatively small. RMS voltage only decreases from 6,000 to 5,980 Vrms.

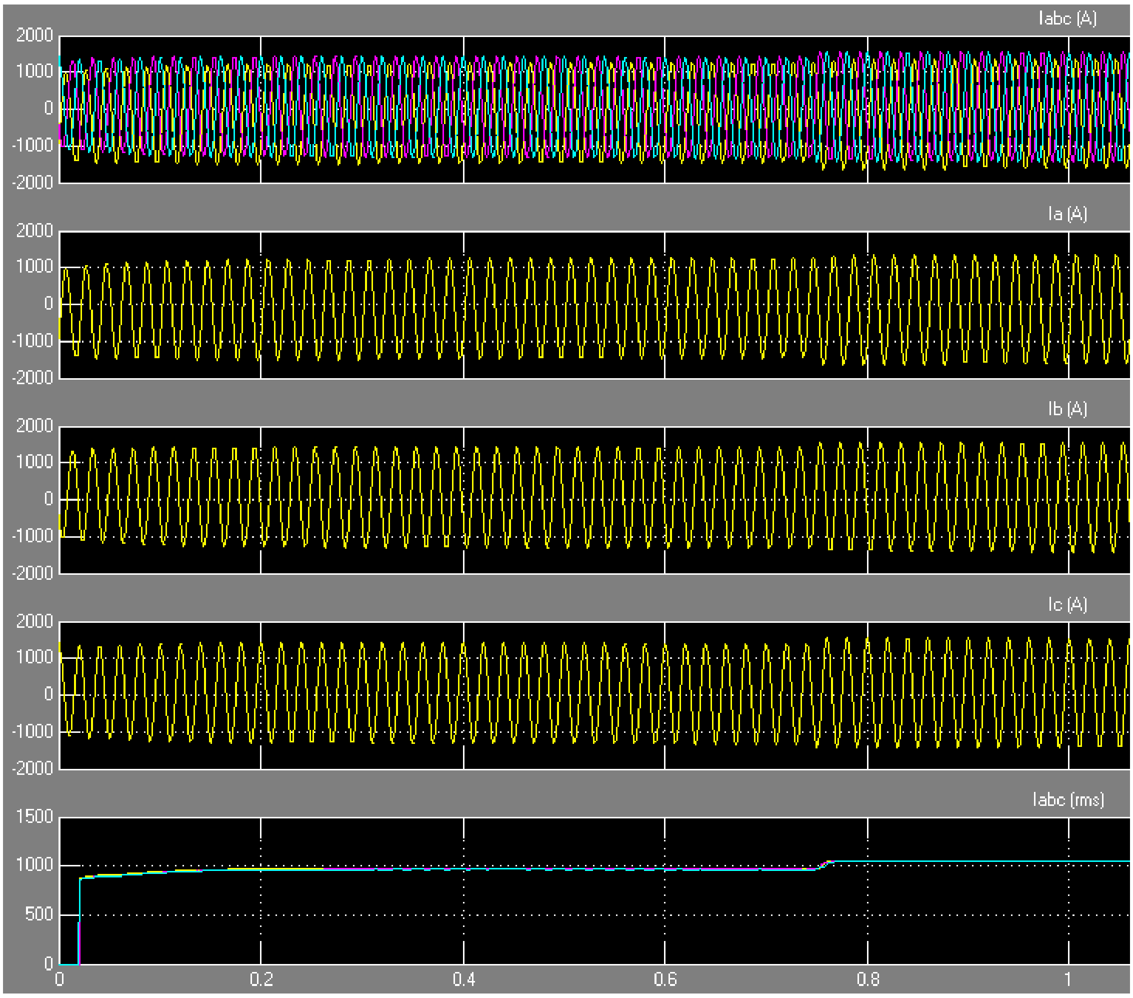

Figure 105: Currents in electric feeder 4 with load increase in electric feeder 4

Effects of the load increase in the currents may be seen at a first look instead. Here there is a growth of the current, and with a closer look it is observed that it rises from a value of 960 Arms until reaching 1,050 Arms.

In electric feeder 1:

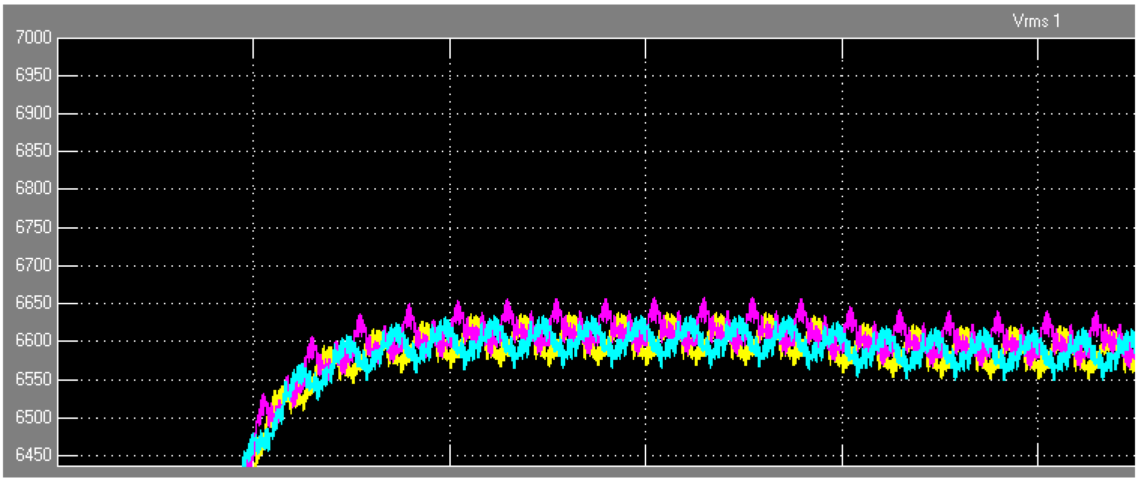

Figure 106: Vrms in electric feeder 1 with load increase in electric feeder 4

A close look at the RMS voltage of the electric feeder 1 makes possible to be aware that there is a small effect of the load increase in feeder 4, but it is barely unappreciable. In Figure 106, it can be seen how the RMS voltage oscillates around 6,600 Vrms at the beginning, with its maximum peaks surpassing by little the barrier of 6,650 Vrms. Then, the axis of the oscillation descends (starting at 0.75 seconds, when the load increase in electric feeder 4 is produced) and consequently, the maximum peaks of the oscillation now don't reach the 6,650 Vrms. The own oscillation of the RMS voltage makes difficult to define the exact effect that the load increase has had in this electric feeder but it exists, although being clearly small.

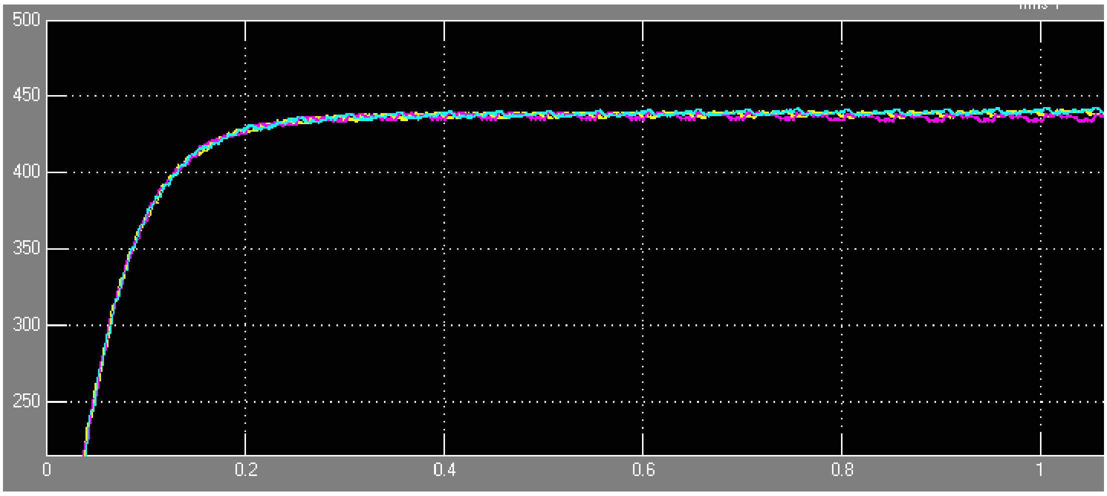

Figure 107: Arms in electric feeder 1 with load increase in electric feeder 4

Regarding the currents, it is noticed that like happened with the load changes in the other electric feeders, there are no noticeable effects in the results.

In electric feeders 2 and 3:

In these two feeders, the results are the same obtained for the electric feeder 1. There is a small effect on the voltage, as the center of the oscillations of the RMS voltage goes down a few volts. Meanwhile, there are no consequences of this load increment in the currents of the electric feeders.

7.7.2. Load decrease in electric feeder 4

In this case, the load of the electric feeder 4 will decrease from 5 MVA to 4 MVA from second 0.75 and forward. The results of the simulation of these conditions are the following:

In electric feeder 4:

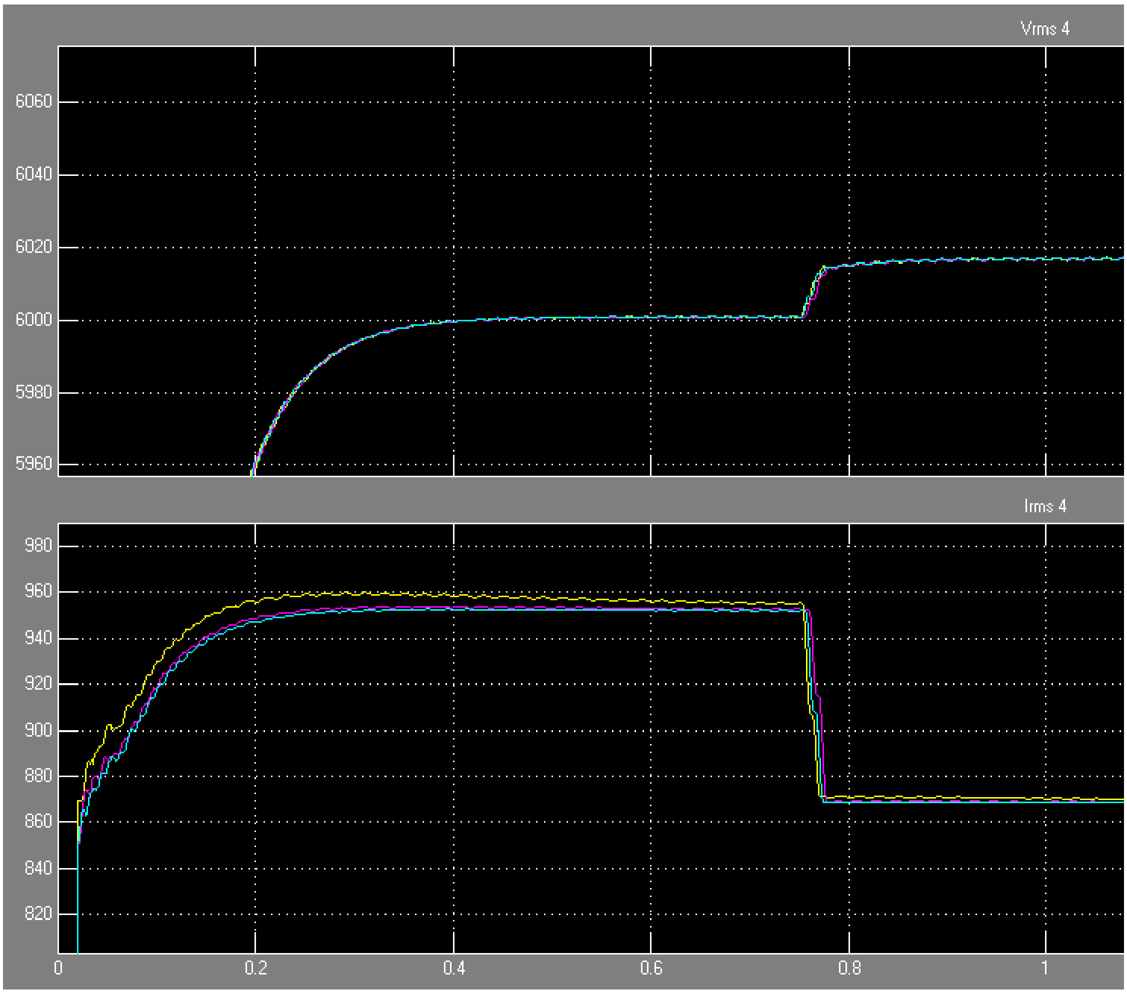

Figure 108: Vrms and Arms in electric feeder 4 with load decrease in electric feeder 4

Like in the previous case of the load increase, the effects in the voltage were too small to be observed at the first look. Although the consequences in the currents were visible, it was also needed a closer view to determine the magnitude of both effects. So, in Figure 108 it can be seen that the load decrease means a RMS voltage increase of approximately 20 V, until it reaches almost 6,020 Vrms. Opposed to it, the current decreases, reaching a value of approximately 870 Arms.

In electric feeder 1:

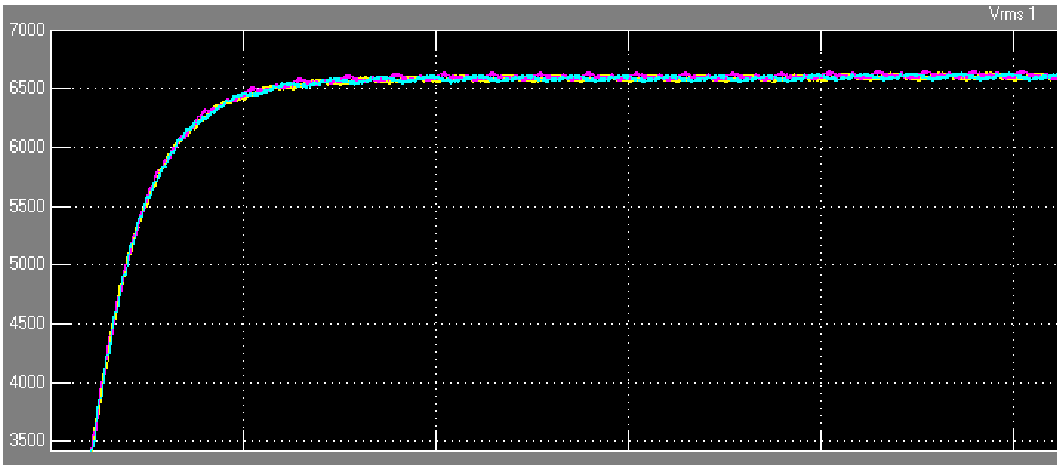

Figure 109: Vrms in electric feeder 1 with load decrease in electric feeder 4

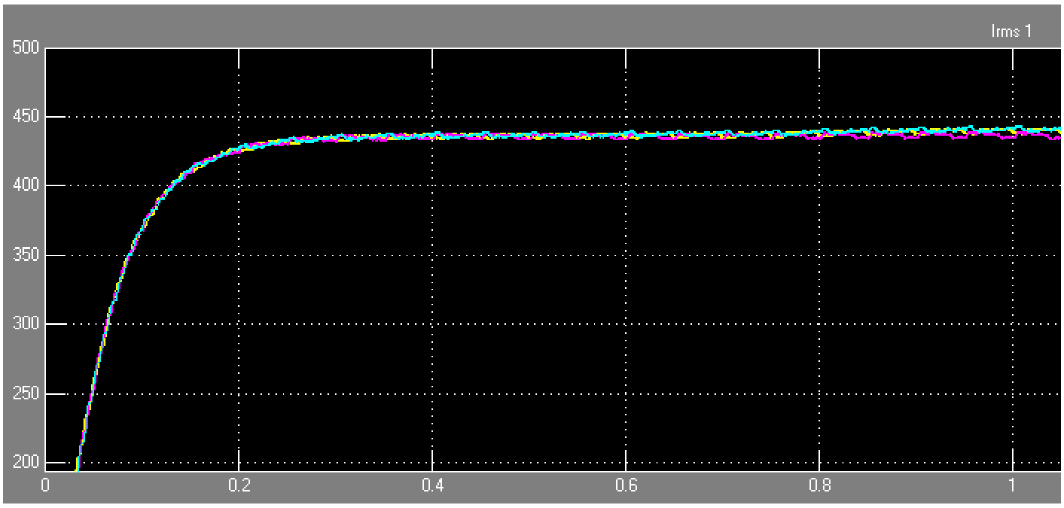

Figure 110: Arms in electric feeder 1 with load decrease in electric feeder 4

Figures 109 and 110 show how the results in feeder 1 are similar to the obtained for the load increase case. RMS voltage of this electric feeder only varies a little bit, although with the load decrease case it is an increment (while it was a decline in the case of load increase). Regarding the currents, the RMS current remains practically the same even with the load change.

In electric feeders 2 and 3:

The same explained for the results in electric feeder 1 apply to the resulting images of the simulations in feeders 2 and 3. The current is not affected by the load decrease, and there is a slight displacement upwards of a few volts of the axis around which the RMS voltage oscillates.

7.8. Short circuit and load changes in electric feeder 3

The last simulation performed includes in the same electric feeder a short circuit, a load increase and a load decrease, one after the other, with the purpose to observe if the three cases combined generate more secondary effects.

This simulation will last 5 seconds, and the short circuit and the load changes will take place in electric feeder 3. The order in which the conditions will be altered is the following:

- At 1 second, the load will increase from 10 MVA to 11 MVA. This will last until second 2, when it will go back to 10 MVA.
- At 3 seconds, the load will decrease until reaching 9 MVA, and it will be maintained in this value until the end of the simulation at second 5.
- At 4 seconds, a short circuit will appear, lasting until 4.4 seconds.

The results obtained of this simulation appear next.

In electric feeder 3:

Figure 111: Vrms and Arms of electric feeder 3 with SC and load changes in electric feeder 3

As it can be seen in Figure 111, during the load increase of 1 MVA between seconds 1 and 2, the RMS voltage decreases while the RMS current increases. They both come back to their original values after 2 seconds, when the load returns to 10 MVA, and when the load is reduced to 9 MVA at 3 seconds, it is the RMS voltage the one who grows and the RMS current, the one being reduced. And then, when the short circuit is produced, the current grows abruptly and reaches peaks of over 4,500 Arms, while the RMS voltage falls to 0. When the connection is restored, both voltage and current stabilize again (although the current has wider oscillations), but the voltage reaches first a peak of almost 10,000 Vrms.

In electric feeder 1:

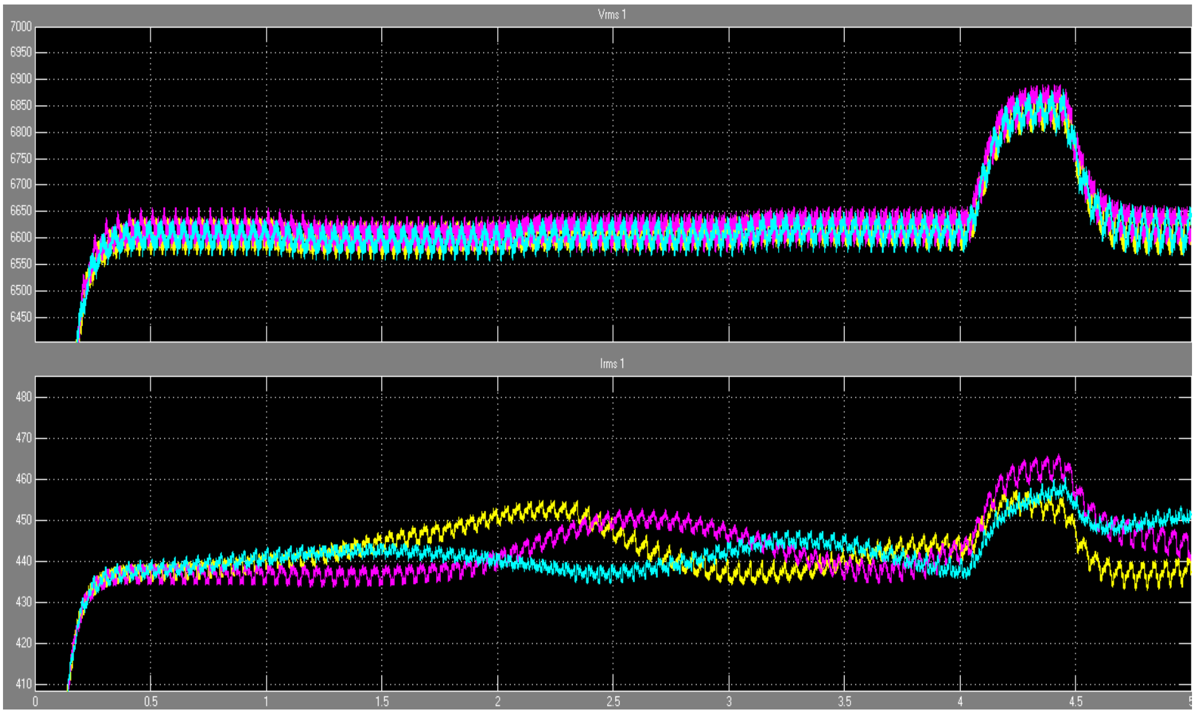

Figure 112: Vrms and Arms in electric feeder 1 with SC and load changes in electric feeder 3

In the previous cases, load changes seemed to have no effects in the voltage and current of other electric feeders (except for feeder 4). However, a simulation with a longer time allows observing two points:

- There is a certain effect in the voltage, although it is only of a few volts. Like it was observed in the cases of load changes performed in electric feeder 4, the axis around which the RMS voltages oscillate moves a little up and down when there are load changes in other feeders.
- The different phases of the current start to oscillate with a very low frequency, in a range of about ±15 Arms.

Besides these effects of the load changes, the consequences of the short circuit are the expected: peaks appear on both RMS voltage and current, and then the values return to its previous state.

In electric feeder 2:

Similar results to the ones obtained in electric feeder 1 are observed here:

- The peaks of voltage and current at short circuit present the same shape.
- The axis around which the three phases of the voltage oscillates goes slightly down when the load increases, and goes up when the load decreases.
- The phases of the current also oscillate, although in a less wide range of ±10 Arms.

In electric feeder 4:

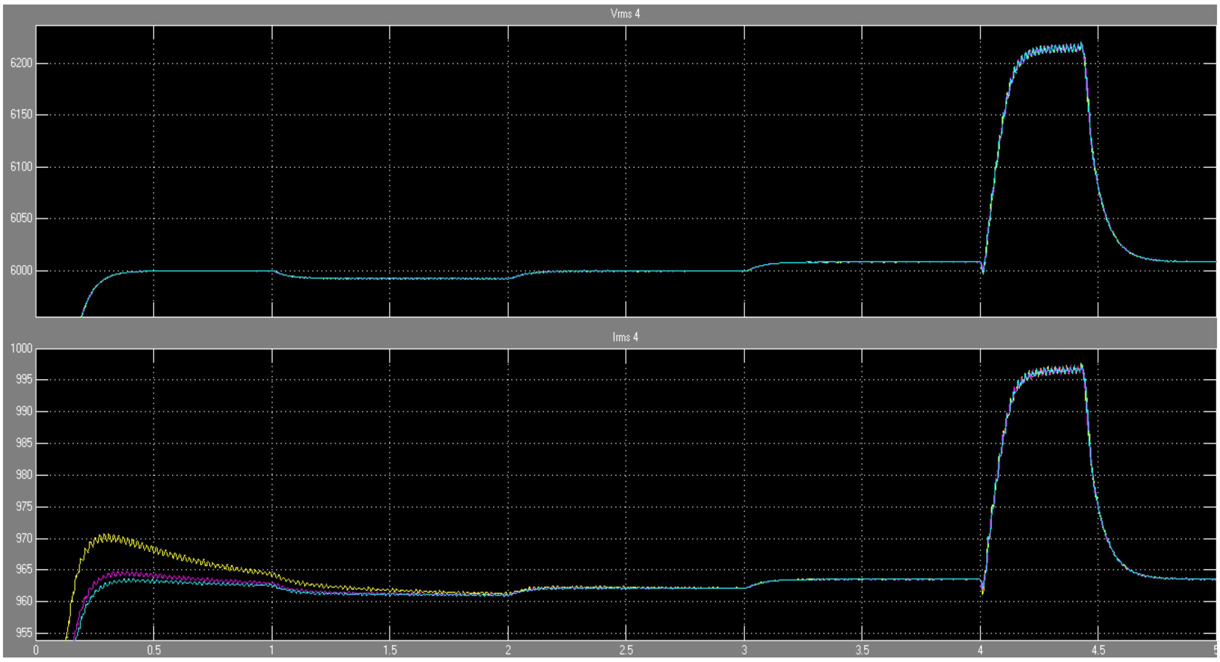

Figure 113: Vrms and Arms in electric feeder 4 with SC and load changes in electric feeder 3

Finally, in electric feeder 4 it can be seen that the effects in the voltage and the current are practically the same:

- RMS voltage and current decrease when the load increases in electric feeder 3, and they increase when there is a decline of the load of electric feeder 3.
- A peak appears during the short circuit, after which both voltage and current return to their previous values.

7.9. General analysis

Through this entire chapter it has been observed that the different cases of load changes and short circuits have various consequences, and these effects change depending on where is happening everything.

Effects may be bigger or smaller, but it is especially important to be sure that they comply with the imposed regulations; in this case, the parameters stablished by the International Standard 80005. Between all the recommendations this Standard includes, there are some related with the maximum variations allowed to be in the electric feeders of the source in certain conditions. Some of these conditions are a short circuit and cases of transient load, so there are restrictions that may be applied.

7.9.1. Short circuit requirements

The Standard states that the maximum current peak that may appear during a short circuit in the source feeder (what has been called electric feeder 4) is of 63,000 Arms. Looking at this value in all the simulations, the values are:

Electric feeder of short circuit	Maximum peak (Arms)
1	975
2	985
3	1,000
4	35,000

Table 9: Maximum current peak

Like it is seen on the table, the higher peak reached during a short circuit is of 35 kArms, when it is happening in electric feeder 4. This is still far from the maximum 63 kArms, so it should not represent a problem for the system.

Also, the standard stablishes that during the short circuit, the maximum current is of 25,000 Arms, during a maximum time of 1 second. The short-circuit currents obtained in the simulations are the following:

Electric feeder of short circuit	Short-circuit current (Arms)
1	975
2	985
3	1,000
4	26,000

Table 10: Short-circuit current

Here appears a problem, as the short-circuit current in electric feeder 4 is of 26 kArms, while the maximum allowed by the Standard is of 25 kArms. However, the International Standard requires that these 25 kArms are the maximum current that is allowed to be during 1 second, and the short circuit in feeder 4 lasts less than 1 second (approximately 0.25 seconds). So, it would be allowed to work under these conditions, always that the short circuit did not last over 1 second.

7.9.2. Requirements in transient conditions

For transient conditions, such as the ones where there are increases and decreases of load, there are also special requirements. These are a maximum increase and decrease of the nominal voltage during these load changes: the maximum increase allowed is of a 20% of the nominal voltage, while the maximum decrease is of 15%. With a nominal voltage of 6,000 V, the final range allowed is between 7,200 and 5,100 V.

The variations in the RMS voltage of the source with the different load changes are the following:

Load change	New voltage (Vrms)
Increase in electric feeder 1	5,988
Decrease in electric feeder 1	6,012
Increase in electric feeder 2	5,990
Decrease in electric feeder 2	6,010
Increase in electric feeder 3	5,992
Decrease in electric feeder 3	6,008
Increase in electric feeder 4	5,980
Decrease in electric feeder 4	6,020

Table 11: New voltatge after load change

As it can be seen in the table, there is no problem with the transient load requirements, as they change in a very small range of maximum ±20 V.

7.10. Results analysis

When a short circuit is produced in one electric feeder of the system, it is obvious that it is going to have negative effects not only in the feeder where it occurs, but in the rest of the electric feeders as well. And these effects are going to be more or less important, depending on where is the short circuit happening.

If the short circuit takes place in electric feeders 1 to 3, the ones equipped with a converting system, the current in the electric feeder will increase quickly to values in the range between 2,500 – 5,000 Arms, while the RMS current in normal conditions is never above 1,000 Arms. And after the end of the short circuit the current will return to its previous values, as well as the voltage (which during the short circuit has gone down to zero), but in the case of the current a side effect will be observed: after the short circuit, the RMS values oscillate in a wider range than before it was produced. For example, the RMS current after short circuit in electric feeder 1 fluctuates between 420 and 620 Arms, while previously it was quite steady around 440 Arms. The ship's systems must be ready to accept these current variations during a certain period of time. Otherwise, after the short circuit was produced the ship should be totally disconnected and connected again, in order to reestablish the right conditions of operation.

With a short circuit produced in one of the three first electric feeders, the effects that are reaching the other loads are not dangerous, as only small perturbations are produced. In the RMS voltage, the maximum alteration caused by a short circuit in another feeder is of 300 Vrms, which is only an increment of 4.5%. This same percentage is the maximum RMS current increase, not bigger than 20 Arms in any case. The consequences of a short circuit in one of these three electric feeders are even smaller in electric feeder 4, as the alterations produced represent even a lower percentage of variation: the maximum increase in this electric feeder of the voltage is of approximately 3%, meaning an increase of up to 200 Vrms, while the variation in the current is of around 2%, which is less than 20 Arms.

But when the short circuit is produced in electric feeder 4, the one that does not have a converting system, the consequences are more important. In the same electric feeder, while voltage drops to zero current increases abruptly to a peak of above 35,000 Arms. Although it is a value still allowed by the International Standard 80005, the only rule regulating the HVSC with a complete approach from shore side (which establishes the maximum short-circuit peak at 63 kArms), when the peak is over the short-circuit current stabilizes at 26,000 Arms, and in this occasion the system must be supervised with accuracy, because the maximum short-circuit current that allows the Standard is of 25,000 Arms during one second. While the short circuit lasts less than one second, the requirement of the Standard is not broken, but if the short circuit lasted longer the current would not be complying with the regulations. The short circuit simulated in this project is of 0.25 seconds, so it still complies with this requirement; but the whole system must be supervised constantly and be equipped with the right protection elements in order to assure that a short circuit produced in electric feeder 4 can't last more than one second. Otherwise, the effects would be too bad for the ship that it is supplying, and the Standard requirement would not be fulfilled.

Moreover, the short circuit in electric feeder 4 is the one having bigger effects in the rest of the feeders. The amplitude of the phases of both voltage and current start to decrease gradually when the short circuit appears, reaching very low values. For example, during the tested short circuit of 0.25 seconds the RMS voltage in electric feeder 1 experiments a decrease of a 66%, and there is approximately the same decrease percentage in the RMS current. The percentage of the decrease seems to grow when the load of the electric feeder is bigger: in electric feeder 3 (which has a load of 10 MVA, opposed to the 5 MVA of electric feeder 1), the RMS voltage drop is of 81%, approximately the same percentage that experiences the RMS current.

Regarding the cases of load changes, it is observed that when the load of an electric feeder is increased or decreased in a big percentage, some consequences appear in the voltage and current of the own feeder. When the load is increased, the voltage is reduced while the current grows; similarly, when the load is decreased the voltage of the electric feeder rises while the current goes down. The main issue caused by these load changes is the deviation that is produced from the 6,600 Vrms that are meant to reach the ship: with a load decrease of 1 MVA in electric feeder 1, the RMS voltage at the ship is of 7,000 Vrms, which represents a deviation of a 6%. And the only way to solve this is by adjusting the parameters of windings 2 and 3 of the transformer in the circuit design, what in the reality would be changing the relation of transformation so it can be adapted to the new supply requirements of the ship.

It can be also noticed that the effects of the load change in the electric feeder are smaller as the total load increases: the consequences of adding or subtracting a load of 1 MVA to the load of 10 MVA in electric feeder 3 are less important than doing the same to the load of 5 MVA of feeder 1. In the case of load increase, the percentage of the RMS voltage variation in electric feeder 1 is of 4.8%, while in electric feeder 3 is of 4.1%, and with the RMS current happens practically the same: the difference of the current is of 60 Arms in electric feeder 1, while it is of approximately 40 Arms in electric feeder 3.

However, the load changes have less relevant effects in the rest of the electric feeders. Load changes in electric feeders 1 to 3 practically don't affect to the others beyond a variation of a few volts; although in current it is seen another kind of consequence, as the phases have an oscillation of low frequency that makes the RMS current oscillate in a range of ±15 Arms. In electric feeder 4 is where the biggest changes can be appreciated in voltage, as a load change in electric feeder 1 produces here a variation of approximately 10 Vrms. There are also effects over the current, but they are only of a few amperes.

When the load changes happen in electric feeder 4 it is easier to observe the caused effects, due to nature of the own feeder, which has steadier conditions than the others. Here, a load change of 1 MVA only means a voltage variation of around 0.3% (a change of not more than 20 Vrms), although the current variation is bigger than in previous cases: it is an increase or decrease of about 90 Arms, which means a variation of 9% of the original current. But in other electric feeders, the consequences are practically despised. In voltage, there is only a variation of a few volts, like in the previous cases, and in the current appears the same low frequency oscillation already mentioned.

8. Conclusions

The HVSC are a very efficient way to reduce contaminant emissions at ports, as many studies have demonstrated. These systems must connect the electrical network of a ship to an electrical grid on shore, and these two usually have different work parameters. This is the reason why there must be a converter system installed on port, able to transform the energy reaching the installations into the adequate electricity for each ship.

This converter system must be formed basically by a rectifier and an inverter, with a DC link joining them. With these elements, the voltage and the frequency generated by an external source can be transformed to the ones needed by any ship connected at berth. But the design of the converter system must be done carefully, as well as the adjusting of the parameters of the different elements, because the existing normative establishes some quality requirements that these systems must fulfill.

The entire HVSC system has been designed in Matlab Simulink, representing a connection that supplies with energy to four ships. Three of them are equipped with converter systems, while the fourth receives the energy directly from the source. Once designed, the system has been tested under different conditions: normal operation, short-circuit situations and cases of load changes. The results of these simulations have been observed and analyzed, so later it has been possible to extract some conclusions.

Under normal conditions, it has been achieved a system that supplies with the right voltage and frequency all ships. But to obtain the correct parameters many trials have been done. While the output frequency may be easily controlled thanks to the PWM generating the three phases, the voltages are harder to control, as they have to be regulated from the windings of the transformers. For each electric feeder supplying the three first ships, the voltages of windings 2 and 3 in the transformers located before the rectifiers had to be adjusted again and again, until finally obtaining the required RMS voltage of 6,600 Vrms in each ship. Once the final configuration is settled, it will work correctly, but only while the initial conditions remain the same.

But when these conditions change, there are some secondary effects that appear in the electric feeders, affecting the entire performance of the system to a greater or lesser extent.

In general, it can be concluded that although a change in the conditions of one electric feeder affect to the supply of other feeders, normally these consequences are not important enough to be considered especially dangerous.

Short circuits in the electric feeders with bigger loads cause more severe alterations than the ones produced in electric feeders with smaller loads, but these variations are still of a very low percentage. The effects of load changes are also quite minor issues, as they don't affect seriously to the system: in this case, as smaller is the total power of the load where the load changes are happening, the bigger are the effects. However, in any case they endanger the operation of the system.

The exception to this is the short circuit in electric feeder 4, as the apparition of this problem leads to a decrease of energy in the entire supply system, besides increasing the short-circuit current to striking levels. This is the reason why special attention must be paid when there is a possibility of short circuit in this feeder, and the right safety measures must be taken to prevent further damage.

In fact, it should be considered if it is convenient or not to have this electric feeder supplying directly the ship without any element in the middle, after seeing the effects that it produces. A converter system like the existing on the other three electric feeders could be installed, even knowing that no transformation of voltage or frequency is needed. However, it works as a filter, protecting the rest of the system from the problems that may happen in this electric feeder, and although it would mean an increase of the cost of the installation, the safety would also be improved.

Another detail that has been also observed is that the load changes affect to the supply of the electric feeder, due to the fact that the ship is requiring a higher or lower power, but the transformer is still adjusted with the parameters that worked providing the right amount of power for the previous conditions. So every time that it is known that is going to be an increase or decrease of the load, it should be warned or communicated from the ship to the shore side, or to the elements that are controlling the configuration of the transformers and their relation of transformation (variable tap). This way, the parameters of the transformer could be adapted to the new supply requirements, allowing providing the right voltage to the ship.

Finally, it must be noticed that no frequency alterations have been detected in any of the simulations. In order to be able to study in deep the performance of the frequency, a more complex model of the system would be needed, which would have to include the kind of primary driving force moving the generators at synchronous speed.

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