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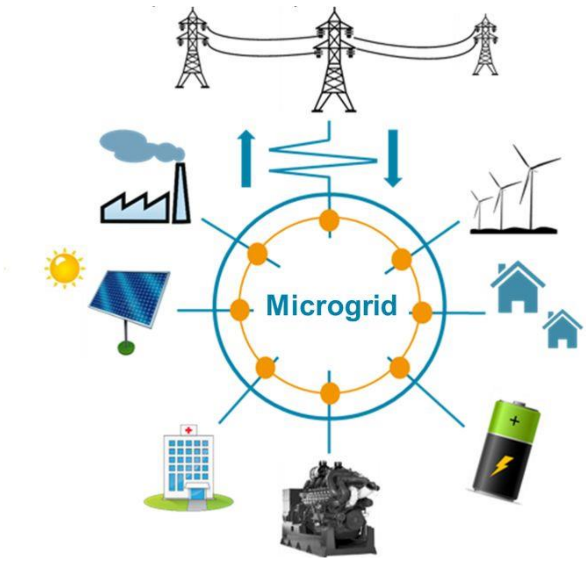
BILBOKO INGENIARITZA ESKOLA
ESCUELA DE INGENIERÍA DE BILBAO

MÁSTER UNIVERSITARIO EN TECNOLOGÍA EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MASTER

MASTER´S THESIS: DESIGN AND MODELLING OF A DC-GRID FOR INDUSTRIAL APPLICATION



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Trilingual summary

Castellano

Para este trabajo de Fin de Máster el tema elegido será el diseño y modelaje de una Microred de corriente continua para un complejo industrial. La transición energética que está ocurriendo hoy en día conduce a la búsqueda de mejoras en el sistema eléctrico de diferentes instalaciones, derivando en la posibilidad del uso de corriente continua en vez de la habitual corriente alterna.

En este proyecto, se tratará de obtener una herramienta que sirva como guía para el diseño y modelaje de una Microred de corriente continua en una instalación industrial, mediante la descripción de diferentes fases y pasos a seguir necesarios para la correcta evolución de un proyecto de esta magnitud.

Esta herramienta estará dividida en 3 fases principales y se realizará un caso práctico en el cual se comprobará la utilidad de dicha herramienta. Aparte del uso de información obtenida por la ODCA, también se utilizarán herramientas de simulación como Matlab y Simulink.

Euskara

Master-amaierako lan honetarako aukeratutako gaia korronte zuzeneko mikro sare baten diseinua eta modelaketa instalazio industrial baterako izan da. Gaur egun gertatzen ari den trantsizio energetikoak hainbat instalaziotako sistema elektrikoan hobekuntzak bilatzera darama, ohiko korronte alternoaren ordez korronte zuzena erabiltzeko aukera sortuz.

Proiektu honetan, industria-instalazio batean korronte zuzeneko mikro sare bat diseinatzeko eta modelatzeko gida gisa balioko duen tresna lortu nahi da, magnitude horretako proiektu bat behar bezala garatzeko beharrezkoak diren faseak eta urratsak deskribatuz.

Tresna hori 3 fase nagusitan banatuko da, eta kasu praktiko bat egingo da, tresna horren erabilgarritasuna egiaztatzeko. ODCAk lortutako informazioaz gain, simulazio-tresnak ere erabiliko dira, hala nola Matlab eta Simulink.

English

For this Master's Thesis the chosen topic will be the design and modeling of a DC Microgrid for an industrial complex. The energy transition that is occurring today leads to the search for improvements in the electrical system of different facilities, resulting in the possibility of using direct current instead of the usual alternating current.

In this project, we will try to obtain a tool that will serve as a guide for the design and modeling of a DC Microgrid in an industrial installation, through the description of different phases and steps to follow necessary for the correct evolution of a project of this magnitude.

This tool will be divided into 3 main phases and a practical case will be carried out in which the usefulness of this tool will be verified. Apart from the use of information obtained by ODCA, simulation tools such as Matlab and Simulink will also be used.

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1. INTRODUCTION

In an era where the global community is continuously seeking sustainable solutions to address the problems of climate change and energy security, the significance of renewable energies has gained the attention of the world society.

However, as the energy transition to this new energy system keeps going forward, the integration and efficient utilization of renewable sources have proven to be a continuous challenge. One promising avenue of research that has gained remarkable recognition is the development of Direct Current (DC) microgrids. These systems, which operate on a localized scale, present a great alternative in energy distribution and management. Unlike conventional Alternating Current (AC) systems, DC microgrids offer higher efficiency, improved reliability, and enhanced flexibility in incorporating diverse energy sources.

Recent advancements in DC microgrid research hold profound implications for the advancement of renewable energy technologies. By providing a platform that helps to interact with the intermittent nature of renewable sources, such as solar panels or wind turbines, DC microgrids create an environment where energy can be harnessed, stored, and distributed with high efficiency. This system also reduces transmission losses, contributing to a more sustainable and cost-effective energy scenario.

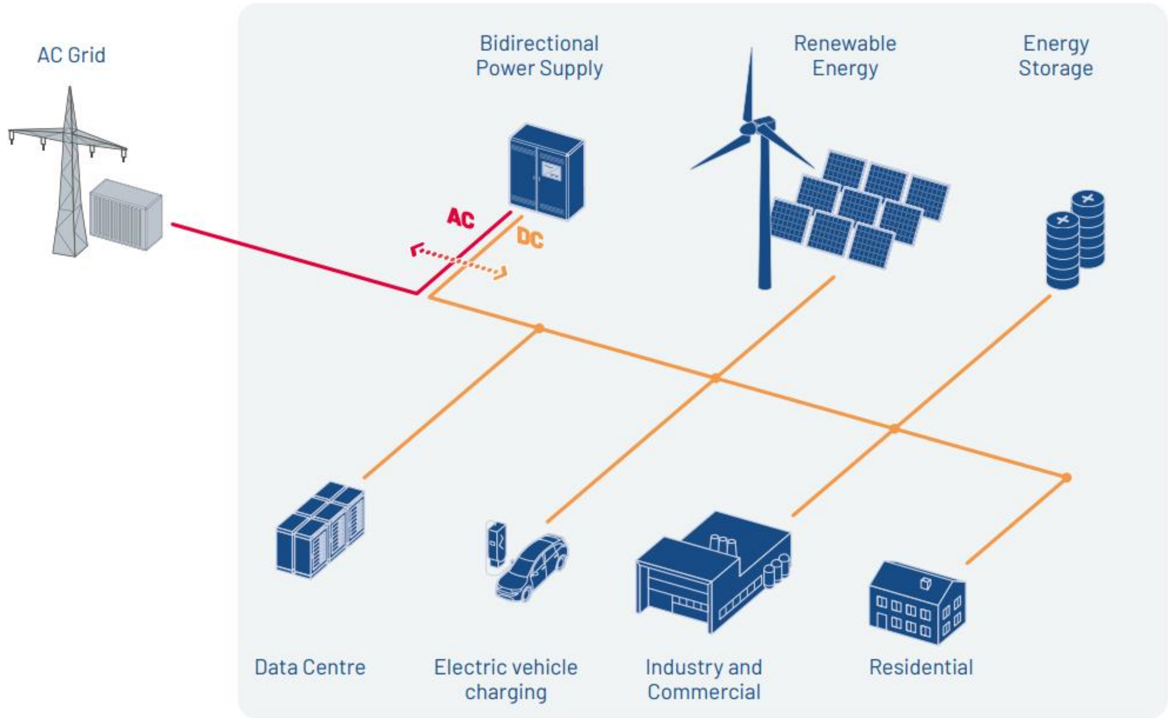


Figure 1: Diagram of a DC grid system (ODCA, 2023)

1.1 Motivation

Even though the DC microgrids offer many solutions for the application of renewable energy in our electrical systems, the implementation of these microgrids has proven to be difficult. Industrial producers are used to the conventional AC systems and have little information on the DC industry, making them reluctant to the use these new microgrids. This is the reason it is so important to investigate and understand how to design a DC microgrid correctly while not forgetting about the usual AC gids.

The advancement of AC grids in recent years has driven them to the front of modern power infrastructure, showing amazing efficiency and reliability. Because AC networks excel at transmitting power over long distances with low loss, they are the favored choice for widespread distribution settings. AC systems' standardized voltage levels smoothly accommodate the vast array of devices powering households, businesses, and commercial organizations, strengthening their role as the backbone of modern electrical networks.

Traditional AC systems include converting direct current power generated by renewable sources such as solar panels and wind turbines into alternating current for transmission. This conversion process results in energy losses, requiring a rethinking of the viability of AC grids for optimizing renewable produce. DC grids, on the other hand, provide more direct opportunities for incorporating renewable energy, potentially lowering conversion losses and increasing total efficiency.

The evolution of alternating current grids has substantially improved electricity distribution efficiency and reliability. However, the growing use of renewable energy and the need for energy storage technologies cause careful examination of grid topologies. While AC grids continue to be an important part of our power networks, investigating the potential benefits of DC grids in terms of maximizing renewable energy generation and perfecting storage systems is critical for assuring a reliable and sustainable energy future.

The design for electric supply systems is structured based on the grid hierarchy in three system levels: the planning process for the transmission grid, the planning process for the distribution grid and the one for power supply in facilities (Darian Andreas Schaab P. S.). Regarding the design on a facility level, the main goal will be to ensure the power quality on the low voltage level. (Darian Andreas Schaab S. W., 2017)

Approaching this design process with the DC-microgrid idea, the planning aims regarding the power generation change. Now, the planning process considers the design of the generation and storage capacity as well as the implementation of an active grid control system to size the flow of power on the grid. (T. Dragičević, 2015)

Although these design processes have been modified to fit with the new specifications of the direct current systems, the approach has not covered all the important and necessary aspects of the system such as the bidirectional selectivity or the local integration of decentralized power integration.

This project will tackle this problem by creating a design system for an industrial site composed of distinct phases. These phases will have small and escalated steps in which the design of the system will be simplified, making it easier to identify possible hustles that the designing process presents. This process will be reduced to easy calculations without dismissing technological accuracy. Also, it will lower the time of design as well as reducing costs and therefore, improving the efficiency of the process.

1.2 Background

In order to understand how the process of designing and modelling of the DC system will happen, the definition of what exactly a DC Microgrid is and a generic diagram of it on an industrial site will be shown. Also, some important aspects that surround the DC industry will be addressed.

The usual DC grid is an open system in the low voltage range, with an operating voltage from 480V to 750V, depending on the system. This system is usually divided in DC sectors, which consist of a functional unit connected to the DC network via a common DC feeder. Also, there is a protection system which includes short-circuit protection and considers selectivity. In some parts of the system, a bi-directional flow of energy is needed to obtain the maximum efficiency of the system, for example on the energy storage or on the AIC (Active Infeed Converter). All elements are connected using a proper cabling system and each of them is at the same time correctly protected with a grounding system.

In the next figure a brief diagram of how should a DC-microgrid of an industrial application is shown:

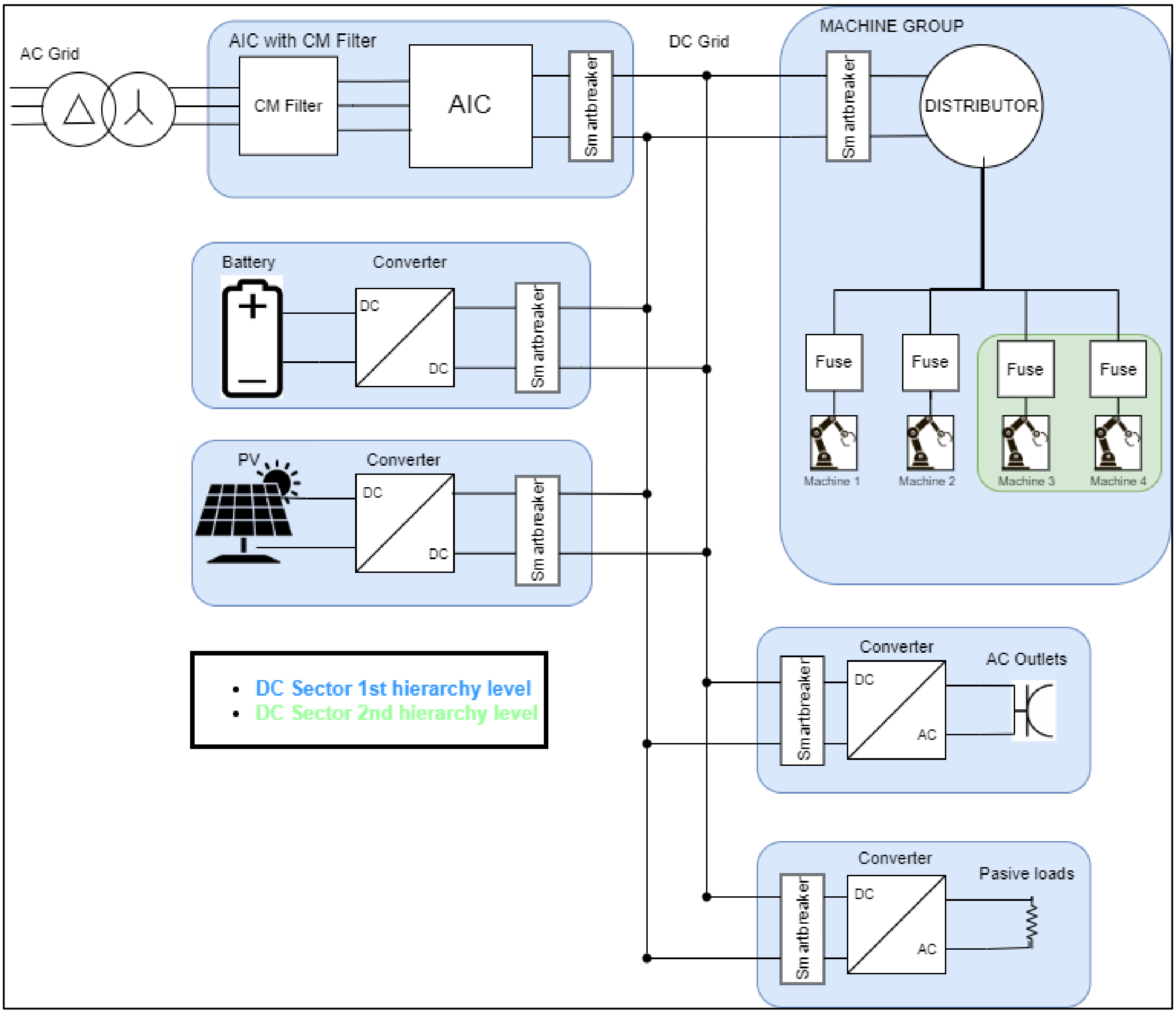


Figure 2: Diagram of DC grid in an industrial site

As it can be seen in figure 2, a common DC-microgrid will usually have the next elements:

- **Active infeed converter**: It is the main device of the MG as it converts the electrical power from the main AC grid to our DC grid with the help of a filter. It will usually have a bidirectional flow, making it particularly useful for the flexibility of the system energy-wise.
- **Storage unit**: A unit to store energy which usually will be a battery or a supercapacitor. It gives the system a source of energy that can be used in case of grid malfunction.
- **Renewable energy source**: This will be one of the sources of energy of the system. Usually, it will be PV or Wind turbines.

- **Machine group**: The main machinery of the industrial site such as production machines and robots gather in this group. This group will be one of the most important ones for the functioning of the site.
- **Passive loads**: This element enlarges all the lighting, heating, and air conditioning systems.
- **Electricity outlets**: Normal AC electrical outlets that can be found everywhere for the connection to the grid of computers, screens, or other type of utilities.
- **Protective elements**: The protective elements will be composed of smart breakers and fuses to ensure safety all around the system.
- **Converters**: These elements will take care of the necessary changes on the grid from AC to DC needed for the system to work.

The correct arrangement of all these elements, with an optimal cabling distribution, the adequate grounding concept and a good protection system in place will create the necessary conditions to set up an industrial DC microgrid. Once the general aspects of a DC microgrid have been described, the objectives of this project will be addressed to figure out about the next steps.

1.3 Objectives

The main objective of this Master´s Thesis will be the designing and modeling of a DC-microgrid system that will meet the power requirements of an industrial application. This main objective can be divided into two parts: First, understanding the presented problem, and then, solving it.

In order to tackle the main objective of the thesis first there must be an understanding of the general problem. The problem of how to find the way of extracting the maximum efficiency out of renewable energy and new storage solutions. Deciphering how to solve this issue on an industrial site with the implementation of the DC-Microgrids will lay the basis for this project.

Once the problem has been analyzed and the DC Microgrid as a solution fixed, a plan to how to implement this Microgrid needs to be made. The aftermath of designing and implementing this plan in a structured way will result in the completion of the main objective of this Master Thesis: Designing and modelling of a DC Microgrid. To reach this objective, a proposal of the steps to follow has been made.

2. PROPOSAL

In this section, a proposal of how the Master Thesis will be structured will be shown. This will help to create a structure that will be composed of the main tasks of the project. Also, it will include a brief explanation of each of the main sections of the document, making it easier for the reader to follow the dynamics of it and help them understand the reasons for realizing these tasks.

The main part of the project will be divided into three phases with the objective of having a more structured mainframe. The first phase will be named "initial conditions", the second phase will be the "concept phase" and the third will be the "Designing and dimensioning Phase". In the next figure, an overview of them can be found:

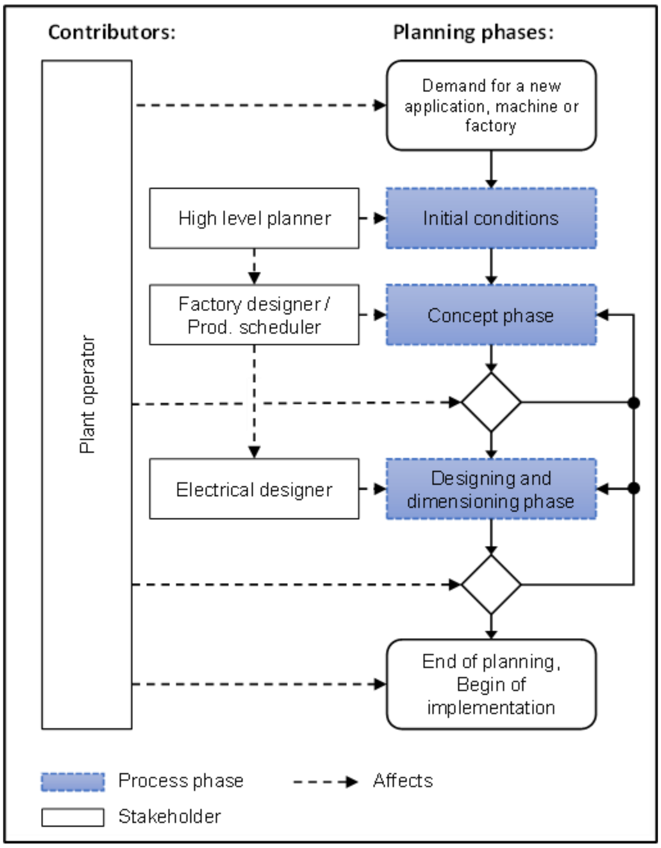


Figure 3: Process overview

A brief description of all of them will be given so that the reader may understand what to expect from each of them.

- **Phase 1:** *Obtaining information about the challenge*: It is important to know what the problem presented by the customer may be to find the best solution to it. The gathering of information about the customers' requirements and initial conditions through the creation of a specialized questionnaire will be the first step of this project.

- **Phase 2:** *Creating a high-level solution of the problem*: Once all the fundamental information of what the customer expects is obtained, the next step will be to start defining a set of concepts, which will comply with the costumers´ requirements. These concepts will include an energy analysis, the selection of a grounding concept, how the link with the external AC grid will be and a first schematic configuration of the DC grid.

- **Phase 3:** *Providing a detailed solution of the problem*: In the third phase, all the components of the grid will need to be arranged, dimensioned, and configured to work in an optimal way. To reach this result, a series of steps will be followed in which the most important designing hustles will be tackled. This phase will follow an iterative method looking for the optimization of the obtained results.

The phases mentioned above will also be divided into subphases. The main reason for this is that there are topics inside this steps that are more suited to be addressed separately and later put back together obtaining the most suitable solution. In the next picture, a configuration of the different subphases and their content is shown:

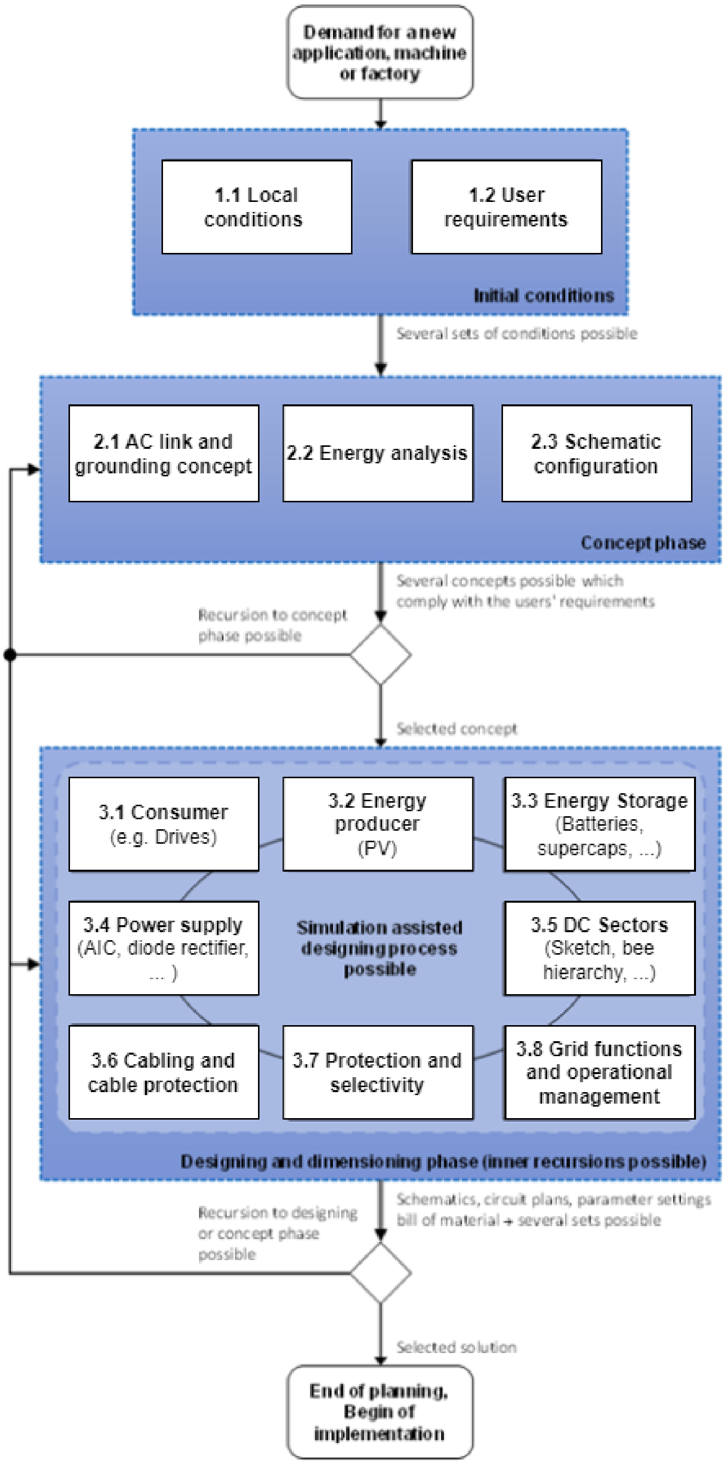


Figure 4: Phases diagram for designing and dimensioning procedure

Once the phases and subphases have been defined and the content of them explained, the model for the designing and modeling of a DC microgrid for an industrial application will be fixed. With the intention of testing and improving such a model, the **application of a real case scenario** seems the most valid option. Although more than one scenario will be explored so that the changes in the main model make sense, only one scenario will be shown on this document in favor of simplicity.

This real case will include a user of industrial background with the need to implement a new DC microgrid on their fabrication system to extract the maximum efficiency out of it. The user will be new to this kind of method so it will serve as a great example and will lay the basis of the development of this kind of system for possible future projects. On this example, all the phases and subphases will be followed to reach a correct design and dimension of the DC microgrid.

Once the method has been tested with the real case scenario, the obtained **results** will be discussed to show how useful has this method proven to be. Finally, an **economic analysis** will be made available so that the reader has a notion if this project is profitable or not. As all the main points of the project have been introduced and described, the next section will be the description of the first phase of the project: Initial conditions.

3. PHASE 1: INITIAL CONDITIONS

Regarding the development of a project, the foundation of achieving success lies in the correct acquisition of information. Before embarking on any project, it is essential to start a comprehensive process of gathering key data and insights. This initial phase will serve as the basis upon which strategic decisions will be made.

As the DC Microgrid is an innovative way of designing the electrical layout of an industrial site, it is likely that the user will not know the correct way of setting it up. The DC MG has some resemblance in some respects to the usual AC grids but there are also new concepts that need to be addressed. To be able to satisfy the user´s expectations, it is essential to have all the information possible about the needs and prospects for the project.

For the purpose of correcting this lack of information, it has been decided to create a specialized questionnaire directed at the customer about the construction of the DC-plant. In such a questionnaire, questions related to the initial conditions of the site will be asked. On the next figure, an extract of such questionnaire is shown to get an idea of the type of questions that are asked (the full questionnaire is shown in the appendix):

1.1.3 Cooling

What cooling options for components are required/available/allowed?

1.1.4 Sound

Are there noise limit values?

1.1.5 PV-Regulations

If necessary, which PV regulations in DE, EU or international should be considered?

1.1.6 AC-Grid-Country

How high is AC voltage, AC frequency? (400V/50Hz, 480V/60Hz, ...)

How good is the current grid stability/quality?

Figure 5: Part of questionnaire for Phase 1

3.1 Procedure and content

The creation of a questionnaire for the implementation of a DC grid on an industrial level involves the understanding of specific needs, concerns, and requirements of the customer. Even though the developed questionnaire can appear very straightforward, there should be a lot of work behind it. It cannot be compared with the usual standards that arise from the designing of a common AC grid. That is why to make this questionnaire a set of requirements is needed.

First, one must be familiarized with the DC industry and be able to understand the implications of implementing a new system that the current industry is not used to. The research about this issue is still ongoing and that can pose a challenge.

There are some main topics that need to be addressed such as general information of the user´s company, the current power infrastructure, DC grid awareness, operational requirements, technical specifications, concerns of the user and possible future considerations.

The goal of the questionnaire is to go straight to the point and make it time efficient for the user, so the questions need to be adjusted to be easily understandable. The user probably will not be able to answer all of them, that is why they should be as clear as possible and have a logical order.

The questionnaire will be divided into two big sections: Local setup and User requirements. These will also be divided into subsections, each of them holding a couple of questions. A brief explanation of each of these sections will be given for a better understanding of the content of it.

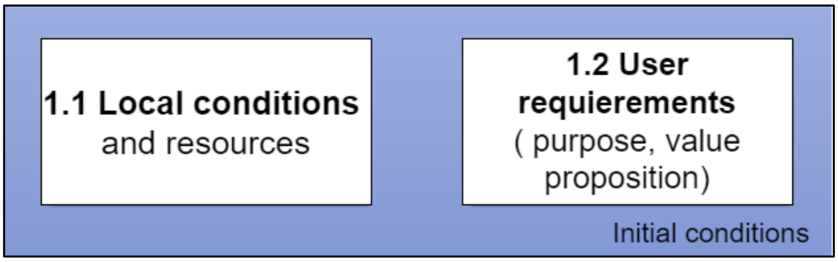


Figure 6: Initial conditions diagram

3.1.1 Local setup

The local setup will hold the first questions that will be asked the user. These questions will relate to what the current situation is. It is a very important part of the process, as it will be the base from where everything will be built. There is a significant difference between starting a project from scratch or already having a location and installed cables, machines, and infrastructure.

The first topic that will be tackled is the existing infrastructure. For the purpose of planning, it is necessary to know what is already done and how to adjust to it. Even if a facility is fully constructed, the DC Microgrid brings a lot of variables which will make it change.

Another important point is the location and distribution of the machines, energy supplies, PV, batteries, …. To correctly dimension the cabling that will unite all these elements, an approximation of the distance between them is needed.

Sound and cooling also will be factors to consider in case there are any special specifications that need to be followed.

Because the AC voltage and the frequency of the grid change constantly depending on the country, questions about them and standard guidelines are also asked. Also, depending on the side of the industrial site and the location where it is planned to be installed, there could be some limitations regarding the total power that can receive in a continuous way.

After this section is finished and a clear view of the existing present conditions is fixed, it is possible to jump on to the next section, the user requirements.

3.1.2 User requirements

The second part of the questionnaire will be focused on the user requirements. For this part the questions are more focused on what the user needs and demands for the system to work. It focuses on the power of the system and how this power should be controlled and distributed in and out of the DC grid.

Every design process starts by knowing the requirements of the users and the purpose they have for the new equipment. In this aspect, the DC Microgrid offers a lot of different advanced solutions and that is the main reason why this information will be so important for this type of grid.

For example, a normal AC grid will be very dependent on a severe power fault of the AC main grid, but this can be avoided with a DC Microgrid. The use of this type of grid can help to bypass AC grid faults because a control system exists, and it is separate from the power supply grid. This system could help bypass energy shortages of microseconds to prevent production stops of a much larger amount of time.

If the end user possesses a more profound understanding of the production cycles, load demands, and production schedules associated with the application, they can furnish comprehensive information to leverage advanced grid functionalities. These functionalities include peak-power-shaving to optimize possible load demands, resulting in a more balanced AC power consumption through the incorporation of an energy storage system. Also, the integration of decentralized energy producers with storage systems can decrease the required AC power consumption, reducing costs associated with AICs (Active Infeed Converter) and wiring.

3.2 Results

The success of the questionnaire will always be linked to the range of knowledge that the user has about their system and how DC grids work. Although all the questions may not be answered, after the questionnaire there should already be an image of what the user wants and how it can be delivered.

From this data collection, different information can be obtained. Mainly and most importantly insight on the user´s perspectives will be obtained. This data will help to identify patterns and trends, by comparing them with other situations. Also, feedback on extremely specific topics that are essential for the design of the DC Microgrid can be obtained.

As the local setup will be described, there will be information about the challenges the user is facing. Therefore, it will be easier to identify the possible areas of improvement. This will help later down the road when offering solutions to these problems.

This information will also create opportunities for follow-up research. This kind of questionnaire sometimes suggests areas that require further exploration or investigation. As DC industry is an emerging and innovative idea, this situation could happen often, helping build a greater net of knowledge and understanding of the topic.

The result of this questionnaire will be the basis for the decision-making process of the design and implementation of the DC Microgrid. It will help make Data-driven choices, reduce uncertainty, and increase the chances of success in the future phases. Making use of all the information obtained from this phase, it will be time to jump into phase 2.

4. PHASE 2: CONCEPT PHASE

Once the information obtained from Phase 1 is gathered and organized, the next step will be to start making use of it. Phase 2, the concept phase, focuses on creating some high-level proposal that will give the user a main idea of what the general system could look like. Aspects such as how the grounding system will be designed, the typology of the main devices or the energy consumption and production will be addressed. These aspects will start forming an idea of how the system will look like.

When designing a DC-Microgrid, there will never be only one possible solution as there are many variables to take into consideration. By the end of this phase, the end-user will be faced with different proposals from which will need to choose in order to advance in the designing process. This proposal's nature will depend greatly on the industrial process on site, the economic limitations of the user and the desired or required level of complexity of the system.

This middle step in the design and modelling of the DC-Microgrid will be divided into three subphases: the concept of AC link and grounding, the energy analysis, and the schematic configuration of the site.

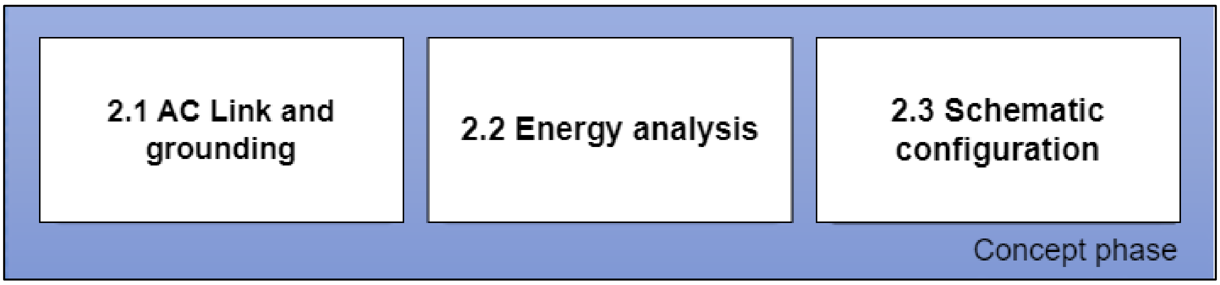


Figure 7: Concept phase diagram

4.1 AC link and grounding

In this section, two aspects of the system will be addressed: the grid interface and the grounding concept. Regarding the first one, the interface of the AC mains, the input voltage of the DC grid and the topology of the power supply devices will be determined. Meanwhile, from the grounding concept, a special type of grounding out of the possible options will be selected considering the best fit for the system. Defining these topics will lay the foundation for the next phases to come.

4.1.1 Grid interface

There exist different options to connect the AC main grid with the DC Microgrid. With the help of information obtained on Phase 1 and knowledge from the DC industry, the connection between them will be defined, as well as the input voltage that will enter the designed DC Microgrid and which power supply device will be used to deliver the power from the main grid into the system. During this selection of features, issues such as EMC requirements, nominal voltage, bidirectionality of power and other important aspects will be considered.

When discussing the connection type to the AC grid, there are different options that will be available depending on the user´s requirements. The power supply of the microgrid will be obtained from the utility company, like any normal grid from an industrial site. The transformer station dedicated to obtaining the power from the grid could be shared by the DC-Microgrid and other AC existing systems, or it could be a station dedicated only to the DC grid. This selection will depend greatly on the possible previous existence of a transformer.

Regarding the value of the input voltage for the DC grid, there are only two options. Either 400 V or 480 V. This is normally set up by the utility company, which will depend on the country where the plant is located.

The last aspect to take into consideration from the grid interface is the topology of the power supply devices. These are the types that could be used:

- **Unregulated feed-in:** This type of feed will make use of a diode bridge rectifier installed to the output of the transformer, converting AC to pulsating DC. It has a simple design but does not bring the most stable voltage output possible.
- **Unidirectional utilities with voltage regulation:** For this option, the bridge rectifier is still used, and a buck-boost converter is included, making the voltage regulation possible.
- **Bidirectional power supplies with voltage regulation:** This last option will consider the needed bidirectionality if regenerative energy is going to be given back to the AC grid. An Active Infeed Converter (AIC) will be the solution for this case.

Although these three options are available, the best and most effective way of exploiting all the functions and advantages that a DC Microgrid has to offer will be the use of an Active Infeed Converter. Even though the other options are also valid power supply devices and will work correctly, the bidirectionality becomes essential when interacting back and forth with the AC main grid, making the AIC primordial.

Once the voltage level, transformer station and topology of the power supply are covered, the section regarding the grid interface is completed, making way to the defining of the grounding concept.

4.1.2 Grounding concept

For a DC Microgrid, the grounding system is essential for safety, system stability and proper functioning. It plays an important role decreasing the risks associated with electrical faults, ensuring the protection of equipment, and safeguarding human life.

There exist several grounding arrangements, each of them having their own characteristics and serving different purposes. The choice of these different types will depend on parameters such as voltage levels, safety requirements or the configuration and lay out of the Microgrid.

Although there are a lot of possible options for DC grounding, having their advantages and disadvantages, in this project only three will be taken into consideration for the sake of simplicity:

- **AC-side grounding on TN-TC-S system**

This type of the grounding for a DC system will have the ground reference via the star point grounding at the transformer of the AC grid. Further low-impedance groundings as connections from L+ or L- to PE are not permitted in the DC grid or in the devices.

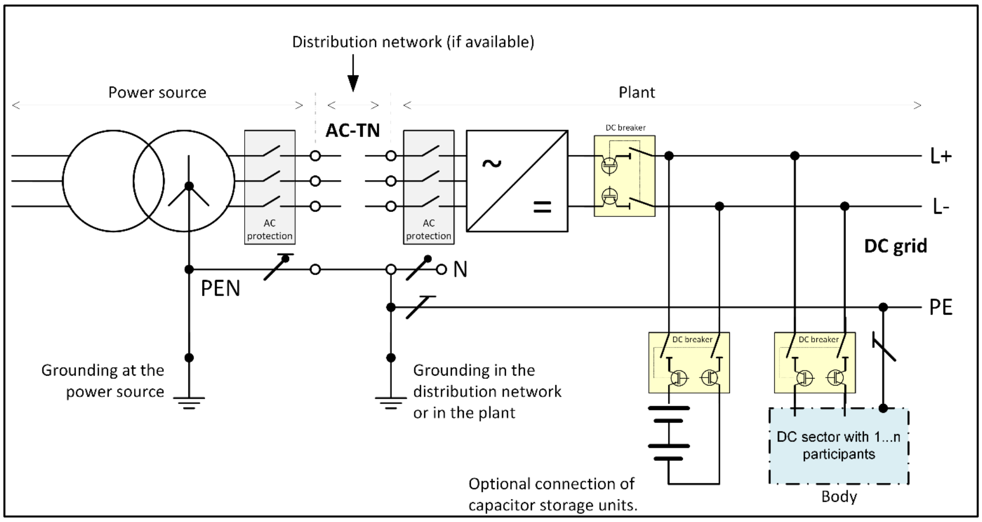


Figure 8: Diagram of DC system with AC-side grounding on TN-C-S system (DC-INDUSTRIE2, 2023)

This type of grounding will have some advantages such as not needing to isolate the transformer, the simplicity of working on an existing AC-TN system and a easy earth fault location. On the other hand, one big disadvantage will be the need of special fast fuse protection in order to protect the power supply from destruction in the event of an earth fault.

- **DC-IT grounding system**

In the DC-IT grid variant, the DC grid is galvanically isolated from the AC grid. The operational grounding on the DC side is done with high impedance from L+ and L- to ground e.g., via resistors or an active balancing.

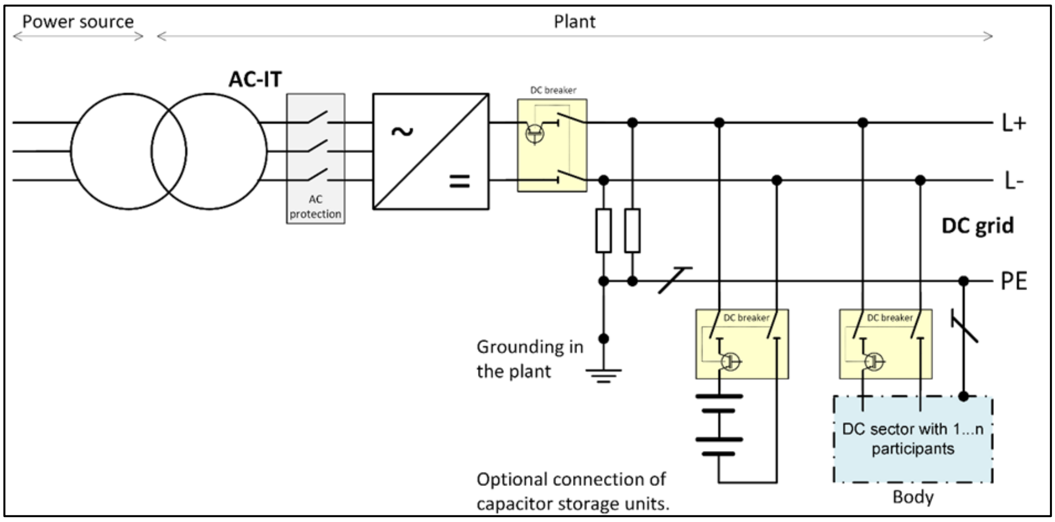


Figure 9: Diagram of DC-IT system (DC-INDUSTRIE2, 2023)

The main characteristic of this DC IT grid is that in the event of an existing ground fault, continued operation is permitted, allowing the system to keep running without stopping the production process. However, the requirements to achieve this are not easy to fulfill.

- **DC-TN-C-S system with midpoint grounding**

With this type of earthing, the center point of the DC voltage is earthed with a low resistance. For example, the supply device must generate two DC voltages that are galvanically isolated from the AC grid, which are connected in series and whose center point is earthed with low resistance.

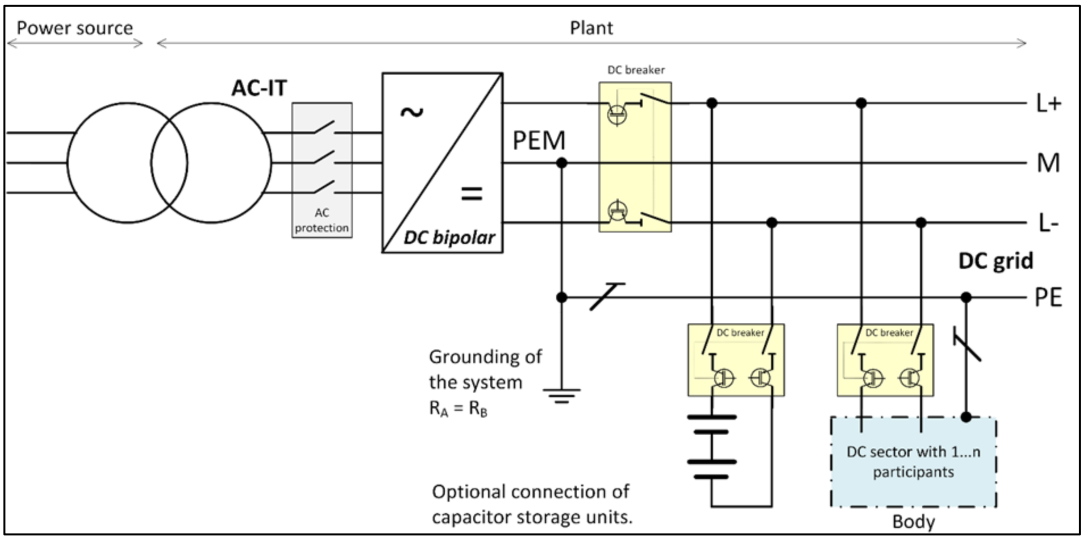


Figure 10: Diagram of DC-TN-C-S system with midpoint grounding (DC-INDUSTRIE2, 2023)

A particular challenge of this concept is that very high DC equalizing currents can occur in the earthing grid due to unbalances when several suppliers are connected in parallel, which is why the DC grid may only be earthed at one point with this earthing concept. Making it not a feasible option for DC Microgrids nowadays. There are also other options that were not included as well, for example the AC low voltage TT grid, being corrosion issues the main reason for it.

Summarizing, the usual decision will be between AC-side grounding and DC-IT grounding. The choice of one of this grounding options and a quick design of how it would be designed will give a close to this section. By stablishing a solid grounding foundation, it gives way to the chance of having a more comprehensive and accurate energy analysis, which will be the next task from this phase.

4.2 Energy analysis

Once the grid interface and the grounding concept have been stablished, one of the most important topics of the system will be addressed: the energy analysis. This section will be key to determine the energy demand, generation, storage capacities and dynamics of the system in order to keep an efficient energy usage.

For this point, the information obtained from the questionnaire of phase 1 will be essential. If a lot of information is given, such as precise power consumption, power sources available and energy profiles of the devices and machines, the energy analysis will give results that improve greatly the efficiency of the energy usage.

There will be three subsections for the energy analysis: the power consumption, the available power sources and the energy profiles analysis and calculations.

4.2.1 Power consumption

The first parameter that will be considered on this energy analysis is the total power consumption. The optimization of power consumption on an industrial setting will not only reduce operational costs but also will lead to process improvements and aligning with sustainable objectives.

From the information of the questionnaire 1, most of the power consumers of the system will be obtained and with the sum of all their nominal power, an approximation of the total power consumption will be obtained.

The power consumers will be divided into three main groups on the next table:

MAIN LOADS (Machines)		PASSIVE LOADS		OTHERS		
Name	Power(kW)	Name	Power (Kw)	Name	Power (Kw)	
						TOTAL POWER (kW)
	Total		Total		Total	

Figure 11: Table for total power consumption

As it can be seen above, the consumers will be divided into main loads, passive loads, and others. The **main loads** will be the essential machines of the system such as the robots or manufacturing machines used in the production process. The **passive loads** will englobe other important devices that are usually running and are not vital for the main production process such as ventilation or lighting. Finally, the rest of the loads that consume power on the system will be placed in the **others section**, making it the section that fits loads such as the AC outlets. The **Total Power** will be obtained from the sum of all of the previous loads.

There are no decisions or calculations to be made in this section as all the loads will already be given by the user. Also, factors such as the potency factor or similar will not be considered in this section. Nevertheless, the value of the total power consumption will help determine some values of the next task, which will be focused on determining the system´s available power sources.

4.2.2 Power sources

This next task will be the choice of the power sources that will be used to keep the industrial site operating uninterrupted. This choice will comply with the user´s requirements as well as the nature of the industry, the energy requirements, cost considerations and environmental concerns.

For the design of the DC Microgrid there will be three main power sources from where power will be obtained:

Main grid

This will be the main source of energy of the system. Although storage and renewable sources are available, the power obtained from main grid should be able at least equal to the total power consumption of the industrial site in case the other two sources are not available.

Because the total power consumption has been calculated on the previous point, the power magnitude of the power supply devices can be set. The rest of the characteristics will be defined in phase 3.

Storage

The storage of the system will be another important energy source for the system. There are key considerations such as the specific requirements of the system, characteristics of the energy flow and desired level or reliability to take into account in order to determine the most suitable storage system. First, the approximate size of the storage will be determined, for later, fixing the type of storage that will be used based on the size. More than one option is available, and the user can decide later what suits them better:

- **Large capacity storage:** The best option for large capacity storage will be the **Lithium-ion batteries** used worldwide thanks to their high energy density and long-life cycle. This kind of storage will play a crucial role in a possible power outage of the industrial site, being able to keep the chain of production running until at least the process is finished. The possibility of **thermal storage** could also appear if it suits the system. This storage system could also help with peak shaving, grid stabilization, better usage of the renewable energy sources and load shifting. This will be the most expensive option as the capacity will be the highest.
- **Medium capacity storage:** A medium capacity storage can also be obtained with a lower capacity **battery** and could have the same uses as the large one. The capacity will depend on the power consumed by the system and the necessary time needed by the user.
- **Lower capacity storage:** For lower capacity storage, the use of **supercapacitors** has become the best choice. This type of storage is often used because of the fast charging and discharging capabilities. They are suitable for small and specific applications inside the system that require quick bursts of power, such as smoothing out the power fluctuations of a machine. This option will be the most affordable option.

Being able to obtain the right balance between storage capacity and the system´s demand will be crucial for an efficient and cost saving system. It will be a task that will be done simultaneously with the modelling of the renewable energy source as they are directly related.

<u>Renewable energy source</u>

The third and last source of power for the system are the renewable energy sources. This energy source makes the DC-Microgrid so interesting as generation and consumption can occur in direct current and originated losses from AC/DC converters can be avoided. In most cases, the renewable source will be Photovoltaic (PV) sources.

PV is one of the most popular and relevant sources of renewable energy as there exists an abundant solar source that does not fluctuate as much as other renewable sources. Also, PV has a reduced environmental impact, and the modular design of the PV systems gives a lot of flexibility for installation. The wide range of applications allows it to be installed in any kind of industrial site, from small factories to big manufacturing facilities.

With the help of the storage system mentioned above, this source will make the system become less dependent on the grid power, making the industrial site more decentralized. It will also lead to energy cost savings once the initial investment is covered as well as being more environmentally friendly than just using energy from the main grid.

On this section, the approximate value of the power that the PV can offer will be estimated. It will also depend on the user, as there could already be enough PV power capacity. If not, an estimate of how much should be installed must be made considering factors such as storage capacity, area for the PV modules and possible future expansions.

4.2.3 Energy usage optimization

The usage of the DC Microgrid with the help of the storage system and renewable sources can help to optimize the energy management of the industrial site. There are a couple of aspects that will be addressed on this point such as peak-power reduction or improvement of energy usage via the analysis of energy profiles.

These DC Microgrids can respond quickly to sudden increases in power demand with the help of an energy storage system. It can store excess energy during the periods of low demand and discharge it during peak times. Also, the use of renewable energies such as solar panels will make use of abundant energy from sunny periods, reducing the reliance of the system in the main grid during peak demand energy timelapses.

In the next figure it can be seen how the mixed usage of storage and renewable sources can keep the power taken from the grid by the system to a minimum saving cost and making the system more environmentally friendly.

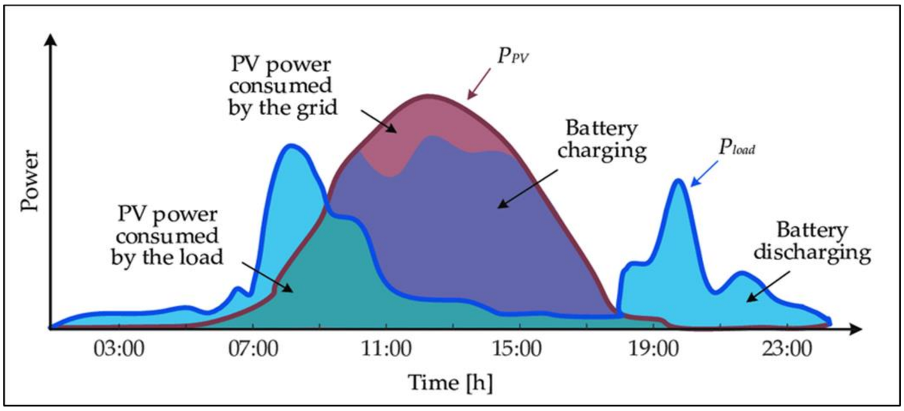


Figure 12: Example of graph of power consumption on a production day (Sandelic, Sangwongwanich, & Blaabjerg, 2019)

On certain occasions, when the user has information about the energy consumption of the machines that will be used such as the energy profiles, it will help to make a more detailed energy analysis, being able to correct some aspects of the system.

For example, if a machine has the next energy profile:

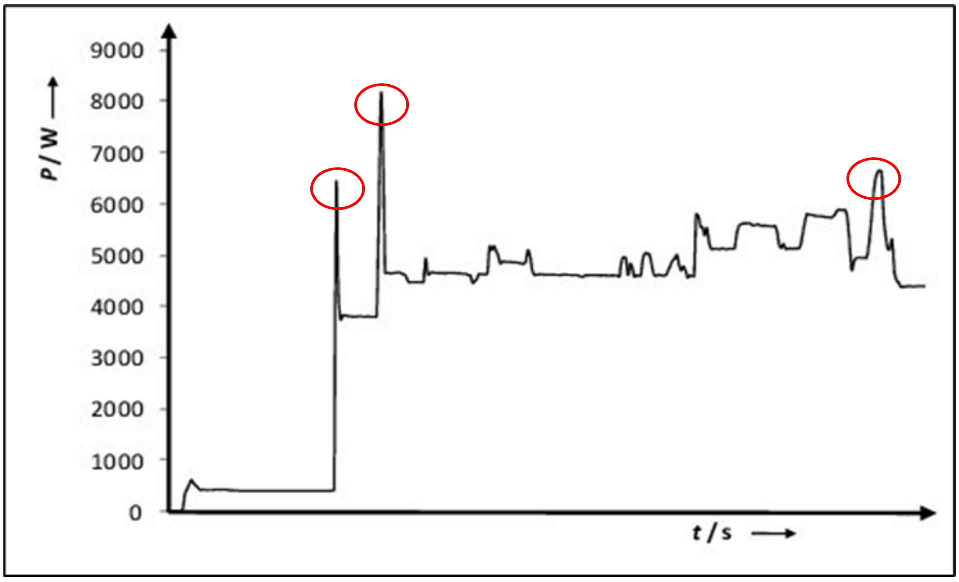


Figure 13: Energy profile of machine

As it can be seen on the figure above, the energy profile shows clear peaks of energy that occur while the normal functioning of the machine. These power peaks could induce a higher demand of grid energy than expected, which could pose a problem for the system.

Implementing energy storages, such as supercapacitors, which thanks to their fast charging and discharging times, can supply energy at the moments of the power peaks, making the system energy efficient.

These energy profiles can also help to design a predictive maintenance practice and apply smart control systems that will help monitor and regulate the machine´s power consumption. An intelligent scheduling can be designed in order to coordinate the timing of energy-intensive tasks and have the renewable energy sources and storage act, optimizing the sequence of operations.

Overall, the DC Microgrid and the elements that take part in it will make the system much more efficient from an energetic point of view, making this a very important point in the process. Once the evaluation of the energy profiles (if given) and the corresponding calculations for the optimization of energy usage are made, a schematic configuration will be done in order to end the concept phase.

4.3 Schematic configuration

Once the main characteristics of the DC Microgrid have been established in previous points, the next step will be to create a high-level diagram in which the main parts of the system are shown. This diagram will help the user to see how the system will look like and what to expect from it. Before entering deeper into this section, a relevant theme that has not been mentioned needs to be introduced to complete the main characteristics, the protection of the system.

Unlike traditional AC systems, DC Microgrids present challenges such as fault detection, interruption, and protection against potential anomalies. From overcurrent protection to fault isolation, the use of devices such as breakers, fuses or smart breakers are essential. Depending on the level of protection wanted and needed by the user, different types of devices will be used which will affect the budget of the project as well as the schematic configuration. Once this is known, the sketch of the system will be clearer.

There is not only one solution for the system, and it can be composed of different elements depending on the expectations of the user, so there will also be more than one possible configuration. Two or three diagrams can be made in this section, encompassing all the possible options and elements previously discussed, such as the size and type of storage, the protection level, or the renewable energy power. This will give the user different options to choose from.

The possible options will be divided by the budget of the user, which will determine how well composed the system will be. In the next figure, it will be shown an example diagram of a middle-sized DC Microgrid with a high budget:

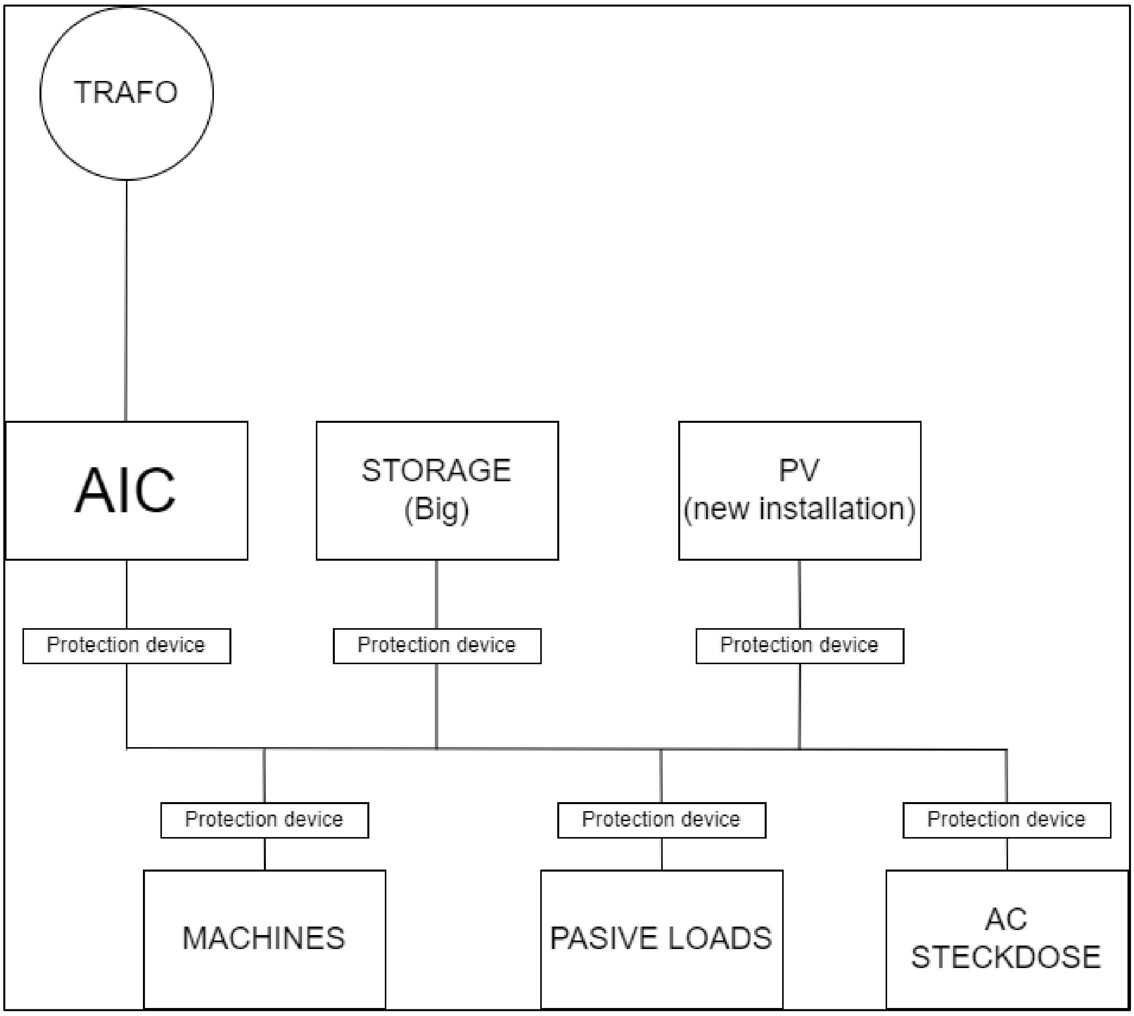


Figure 14: Example of sketch of proposal for DC Microgrid

The sketch will be followed by a table with the main characteristics of the elements:

Main characteristics	
Elements	**Information**
Budget	High
AIC	1 MW bidirectional
Storage	Big/Litium battery/ 500 kWh
PV	Old: 200 kW + New: 300 kW
Protection	Full protection (Smartbreakers)

Figure 15: Table of characteristics for previous DC Microgrid sketch

The sketch shown above is just one of the options that will need to be presented to the user. There are more options that are more budget friendly, which would change characteristics of the system like a lower storage capacity or a less reliant protection system.

Once the different sketches with the corresponding budgets and characteristics are defined, one of the options will be picked for the user in order to finish with the concept phase. Once the first two phases are finalized, with all the basic information gathered, it will be time to jump into the designing and dimensioning phase: Phase 3.

5. PHASE 3: DESIGNING AND DIMENSIONING PHASE

The third and last phase will be the final solution for the user. It will give a detailed solution of how the DC Microgrid should look like and will be focused on arranging and configuring all the components that compose the DC Microgrid.

This phase will be composed of eight subsections that will be focused on different aspects of the designing and dimensioning of a DC Microgrid. Because of the impact that these phases may have on each other. even though they will follow an order, an iterative process will also be implemented in order to achieve the best result possible.

The design and modelling phase includes selection and sizing of components, including energy storage systems, renewable energy sources, cables, converters, and protection devices. Advanced simulation tools will also be employed to model the interactions between the elements and in this case, mostly on the protection and selectivity of the system.

This phase will allow the user to determine the possible behavior of the DC Microgrid under different operating conditions, allowing to refine it to meet performance objectives and ensure a secure and efficient power infrastructure that will support the industrial site without fails.

Before jumping on the eight subsections of the phase, in order to conduct a correct designing process more specific information than the one obtained from the questionnaire in phase 1 will be needed. In order to obtain that, a new and more precise questionnaire will be carried out.

This new questionnaire will carry more specific questions about information needed for each of the phases. In the next figure it can be seen an example of the kind of questions asked. The rest of the questionnaire can be found on the appendix of the document:

3.4 Active infeed converter

Is there any plan of expansion in the future?

Is redundancy needed?

3.5 DC Sectors

What dependance exists between the loads?

Is there a cluster of loads?

3.6 Cables and cables protection

Is there any floor plan?

What will be the ambient temperature of the industrial site?

Figure 16: Questionnaire for Phase 3

Once the questionnaire is fulfilled, the first sections will have the goal of designing the main elements of the DC Microgrid such as the consumers, energy producers (PV), storage systems and the Active Infeed Converter. It is essential to properly define these elements because each of them will form a DC Sector, which will be the next aspect to take into consideration.

After the DC Sectors are defined, cable modelling will be tackled and the protection of the system as well as the cables will also be addressed. In order to design a suitable and proper protection system, selectivity will also be considered.

Finally, the topics of grid functions and operational management will be reviewed. On this last topic, as it is a very extensive area, only the main and most general aspects will be overviewed. On the next figure, the different sections and their order are shown:

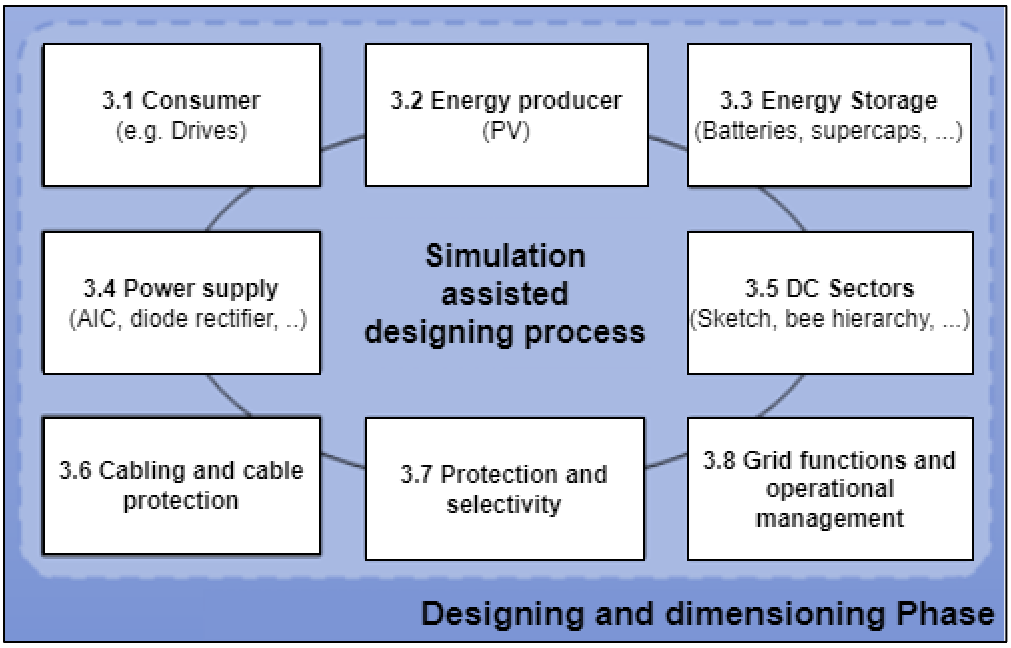


Figure 17: Designing and dimensioning phase diagram

Each section will follow a set of steps that have been divided into flowcharts. These flowcharts are located in the appendix of this document as a help for the reader to understand the thinking process of each section and the tasks needed to fulfill them.

5.1 Consumer

The first subsection of Phase 3 will be directed to the power consumers of the system. It is imperative to correctly define this aspect as all of them will need to work properly in order for the industrial site to be able to complete production processes.

The main task for this part will be to separate the loads in different groups so that they are easier to organize, taking into account their role in the production and the direct or indirect relation that they may have between each other. Also, some parameters will be calculated if possible, such as the voltage or current that will flow through them. By the end of the subsection, a table with all the loads of the system should be obtained with the main values of them and a coding that will help to organize them later.

The industrial site will logically have many loads that will need to be powered. Some of the loads will be more important than others as they will be essential for the main production system; others will just have an auxiliary function. Also, there will be some loads that depend on each other while others will be fully independent from the rest.

The first step will be to identify **applications** or **production cells** that the system may have. The different cell groups will be divided by numbers: cell group 1, cell group 2, ... This production cells will have a cluster of loads that will probably need to stick together. This kind of information will help later with the DC Sectors and the protection system.

After the production cells are defined, the **dependency** between them needs to be stablished. This dependency will have different levels of importance. A table with simple coding to separate them can be seen in the next figure:

Coding	Dependency scale
A	Necessary
B	Big influence
C	Small influence
D	No influence

Figure 18: Table of dependency scale for loads

Once the dependency has been stablished, two paths open up. If two or more production cells are totally dependent on each other, first they will need to be analyzed and later the loads inside each of this groups. On the other side, if some production cells or loads have no influence on the rest, the loads of that cell can be analyzed directly.

While separating the loads, there will be two groups, the main and auxiliary. An example of a main load could be a motor of a production machine while an auxiliary load could be the vents of the ventilation system.

Loads	Motors, controllers, ...	Main Loads (a)
	Vents, HSDC, HSAC, Steckdose, ...	Auxiliary Loads (b)

Figure 19: Table of the coding for differentiating loads

Once all of the loads have been separated and coded, it is time to analyze their information and calculate some basic parameters. For this task, it will be helpful if the user is able to facilitate a load profile that will give information about the power consumed during a certain period of time. If a load profile is not available, at least a load factor should try to be obtained.

With this load factor, values such as the average power and current can be calculated. If this value is not given, only the nominal current and power will be obtained which will make the design of this system less efficient.

In order to calculate the current, because the voltage value will be a fixed and known value which will vary on the load, the only value needed will be the power of the load. In the next figure a table with an example of how a load would be categorized is shown.

Name of the load	Production cell	Dependency group	Load group	Installed Power (kW)	Load profile	Voltage (V)	Load factor	Current (A)	Average Power (kW)	Average Current (A)	Code for the load
Main motor of machine	1	A	b	25	-	650	0,8	38,46	20	30,76923	A.1.b
...											
...											

Figure 20: Table for loads of the system and characteristics

The table shown in the figure above, will help with the understanding of the systems power needs and help in other sections of the phase, specifically in section 3.5 DC Sectors, which will be focused on organizing the loads in different groups depending on the requirements of them. But before that section, other important elements of the system need to be defined, such as the energy producer.

5.2 Energy producer

In this section, the energy producer of the system will be selected, described and some main parameters to take into consideration mentioned. The energy producer of a DC Microgrid has a very important role as it is responsible of generating and supplying power to the grid and in cases of failure in the main grid, it may need to be the only energy source that with the help of a storage system can keep the industrial process of the site running.

There is a diverse range of technologies that could do the function of energy producer for a DC Microgrid, such as solar panels, wind turbines or combined heat and power (CHP) units. For this project, it has been decided to focus the attention on solar panels, as it is the most common technology used by the industry.

Photovoltaic (PV) systems play a crucial role in DC Microgrid, offering a sustainable and efficient means of energy generation. Their technology converts sunlight into electricity by generating DC current electricity, aligning perfectly with the nature of the DC Microgrid. This characteristic coupled with modularity, scalability, and environmental benefits, make PV key for the shaping of the DC Microgrid. Because of this importance, it will form a DC sector by itself.

Although PV is one of the most efficient and currently used renewable energy resource, there are some limitations when it acts as a power supplier. The intermittent nature of the source makes it impossible to deliver a power supply during a prolonged period of time without the help of other elements such as energy storage devices. In the next figure it can be seen the energy profile of a PV panel for a day:

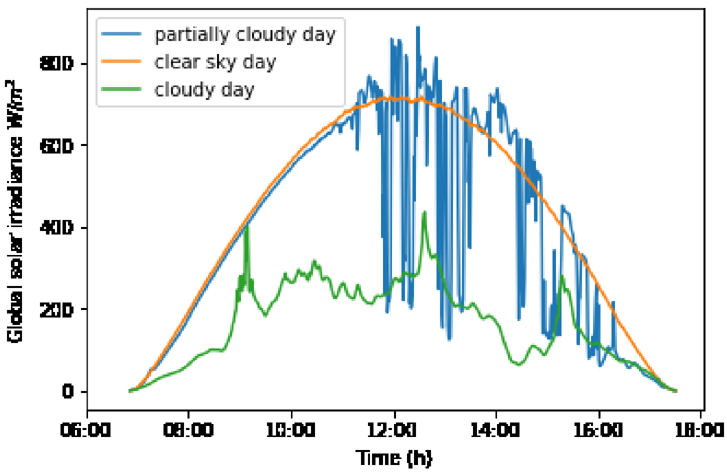


Figure 21: Graph of solar irradiance per hour on a day with different meteorology (Lazola Javu, 2019)

The solar irradiance will be a very important factor as it states how much power is available for the PV to absorb. As it can be seen in the graphic of the figure above, it depends mostly on the time of the day, and it also variates significantly depending on how cloudy the sky will be.

This issue coupled with grid integration, land use and technological limitations still poses a challenge for the PV systems, that is another reason for DC Microgrid research and implementation, with the help of a competitive energy storage system, trying to extract the maximum efficiency possible nowadays from the PV systems.

The value of installed PV on the industrial site will be determined by factors such as the space, necessity of power and available budget. Before any power value is fixed, the performance and efficiency of a DC system needs to be checked in order to obtain the real usable power obtained from this energy source.

There will be two factors to take into consideration: the capacity factor and the performance ratio. Each of them will be defined by different parameters of the system. For the capacity factor this are the main parameters:

- Solar irradiance
- System design and orientation
- Shading
- Inverter efficiency
- Weather conditions

After taking all these aspects into account the capacity factor can be deduced, which usually will be between 15% and 25% for a normal grid. In this case, because of the use of a DC Microgrid, there will be less energy losses involved thanks to the absence of an inverter to swift from DC to AC, making this percentage to be higher than normal.

Also, the usage of an energy storage system on the DC grid will make this factor to vary. Making use of the storage system, effectively shifting energy consumption from low solar generation to high solar generation will lead to a notable improvement in the capacity factor. The size of the storage will also play an important role on this, as a large capacity system will be able to accommodate a higher percentage of excess energy.

Therefore, the value of the usual capacity factor could not be applied in this case as the DC-Microgrid offers a lot of advantages that will make the factor´s usual value to change. A deeper analysis should be made in order to obtain a more accurate value of this parameter.

On another note, the other important value to obtain the usable power from the installed value will be the performance ratio. The performance ratio will depend on the next parameters:

- Temperature
- Soiling
- System efficiency
- PV Panel Quality
- Availability and Downtime

This ratio´s usual value will be between 70% and 80%.

Once these two factors are fixed, this would be the way to calculate the real usable power out of the installed capacity:

$$E_{usable} = P_{installed} \times CF \times PR \times T$$

Figure 22: Equation for the obtention of usable energy

Where:

- E_{usable} is the total usable energy (in kilowatt-hours, kWh)
- $P_{installed}$ is the installed capacity of the PV system (in kilowatts, kW)

- CF is the capacity factor (decimal)
- PR is the performance ratio (decimal)
- T is the time period for which the energy will be calculated

Once the usable power is calculated, which will have some influence on the energy storage designing and maybe on the active infeed converter, DC-DC converter will be defined for the PV system.

In order to choose a DC-DC Converter for a PV system, several factors need to be considered to ensure efficiency, compatibility, and a reliable performance. Some of the key considerations are the next ones:

- Power rating
- Input and output voltage range
- Isolation
- Protection features (will be discussed in further points)
- Standards and certifications

Consulting datasheets as well as technical specifications should be the main tasks to be undertaken for choosing the correct DC-DC Converter.

Once the DC-DC converter is chosen, the section corresponding to the energy producer will be done, with the exception of the protection. The protection concept will be tackled further, and it will involve this element of the system. Because of their direct working relationship, the next element to be studied will be the energy storage system.

5.3 Storage

In this section, the energy storage system will be selected and the size and type of it, determined. There will be some factors to take into account when defining these two parameters. The storage system will be one of the most important elements of the DC Microgrid, so it will be very important to design a system that can make the DC Microgrid to work on the most efficient way possible. As it was shown on the last section, for an efficient way of making use of the power generated by the PV, the storage has a key role.

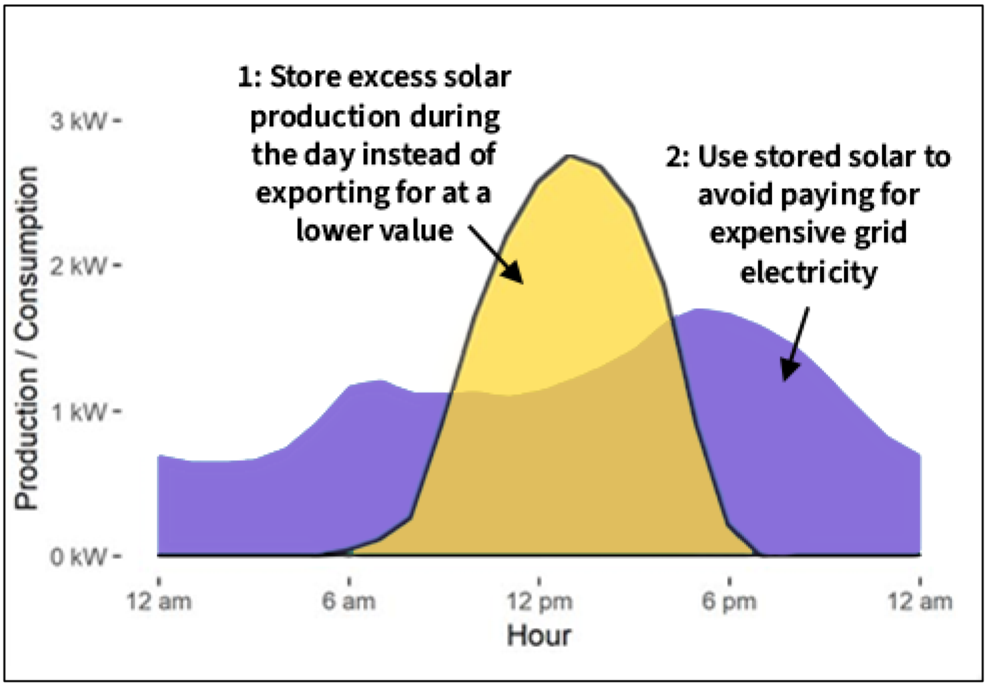


Figure 23: Graph showing the combined working of PV and storage system

In the figure above, a clear example of how the storage system and the PV are expected to work during a normal production day is shown. When designing the energy storage, the total power output of the installed PV should be taken into consideration, as well as other factors.

First, taking into account the system requirements and objectives, as well as the energy analysis obtained from Phase 2, the exact energy storage capacity will be fixed. There is some work done in this aspect, as the capacity´s approximate value has already been defined. In this section, a more precise value will be given, taking into account the answers to the questionnaire in Phase 3. After that, the type of storage will be confirmed, with the possibility of having more than one unit. Finally, details surrounding them will also be addressed, like the DC-DC Converters needed for them or their location on the DC-Microgrid.

In order to obtain the exact value of the capacity of the energy storage, the time needed for the industrial process in case of failure from the main grid is essential. Depending on if the value are microseconds, seconds or minutes, the value of the capacity will increase accordingly.

For example: The mean time of a production cycle of the industrial site is 25 minutes. The machines involved in this process are 6 robots of 30 kW each and 2 conveyors of 10 kW each. With these values, a reasonable energy storage can be designed, to maintain the process running in case of blackout.

Using the following equation:

$$Energy\ (kWh) = Power\ (kW) \times Time\ (h)$$

Figure 24: Equation of capacity for storage system

$$E = \big((30 \times 6) + (10 \times 2)\big) \times \frac{25}{60} \approx 83{,}33\ kWh$$

Taking into account that the storage system could have an efficiency of 90%, a 100-kWh energy storage system could be a smart solution for this case. This cannot be definitive, because other factors such as the renewable energy source´s power is also important, as a big storage system could be needed in case of having a high capacity of renewable energy generation.

Another important task of the storage system can be to reduce the power consumption peaks generated by machines on the site. The solution to this problem is usually solved with supercapacitors dedicated specifically to the mitigation of this phenomenon. In order to be able to solve this problem efficiently, an energy profile of the machine or cell will be essential. In this case, if the information is accurate, the best course of action would be to install a supercapacitor next to the machine or machine group and calculate the value of the needed capacity with the help of the energy profile.

Usually, the energy storage system (at least the general one) will form a DC Sector of its own with the addition of a DC-DC Converter and a protection device for it. Once the exact size and type of storage are defined, the DC-DC Converter will be selected, putting an end to this section of the phase.

5.4 Power supply

Since the beginning of this project, the main focus has been on the controlled DC-grid supply, making the Active Infeed Converter an essential and indispensable tool to achieve this. On this section, the Active Infeed Converter (AIC) will be designed and modelled. There is some work already done on the first section on Phase 2, with the decision of the topology, already fixing some characteristics. For this task, parameters such as the grid codes, island grid, power request and filter of the AIC will be analyzed.

The Active Infeed Converter fulfills a primordial role in enhancing the stability and efficiency of a DC Microgrid. It will be the device in charge of controlling the power flow within the Microgrid, by adjusting the voltage and current levels, it will facilitate bidirectional power transfer, allowing an efficient use of energy distribution with the help of the renewable energy source and energy storage system. This level of control is indispensable in DC Microgrids. This will make the designing of it of outmost importance.

In order to start designing the AIC, first of all, a question needs to be asked: Are there **Grid codes** available for the system? The grid codes are a set of technical specifications and requirements that ensure a stable and reliable operation of the main electrical grid. The impact of these codes in the AIC is direct as it is the main device that connects the DC Microgrid to the main grid. There are some different ways in which the grid codes can affect the AIC:

- Voltage and frequency regulations
- Power quality requirements
- Anti-islanding protection
- Grid support functions
- …

These codes will be essential for the later implementation of aspects such as the island grid or the feed-back energy given to the main grid. If the grid codes do not give green light to the bidirectionality of the AIC, then the only aspects to solve will be power request of the AIC and the filter used on it.

If the grid codes allow for the DC grid to have bidirectionality and it is feasible with the system, the next concept to explore will be the "island grid". The **island grid** term will refer to a situation in which the DC Microgrid operates independently from the AC main grid, creating a self-sustainable system. This is possible with the help of the renewable energy source and energy storage system.

In order to have the possibility of being able to change into "island grid mode", the grounding system that is being used is important, as not all of them will allow for a smooth continuous operation of the DC grid. Depending on the grounding system, different considerations will will hace to be taken into account, that could possibly change the design of the system by introducing protection devices or current sensors.

A DC Microgrid with islanding capability will be very valuable in certain scenarios such as possible disruptions on the AC main grid or when isolation from the main grid is needed because of maintenance. It could also have the function of facilitating providing power in remote areas or critical infrastructure applications.

Once the island grid concept has defined, and defined if it is possible for this system or not, the **power request** needs to be calculated. In order to design the AIC, the value of maximum power that is needed from the AC main grid will be determined. This value will be obtained from the energy analysis of Phase 2.2.

Although there are other power sources such as the storage system or the PV, the AIC should have enough power to supply all the energy needed from the consumers, as these other power sources could not be available at any moment. That is why the power value of the AIC will always a little bit higher (to take into account efficiency or possible energy losses) than the total power consumed by the system.

Finally, once the power request is decided on, the designing of the **filter** for the AIC will be tackled. The biggest disadvantage of conventional AIC without common-mode filters is that the generated DC voltage has a high frequency common-mode against PE that will lead to high leakage currents or high interference emissions. This problem can be solved with a common mode filter.

This device will attenuate the high-frequency voltage components of the common mode voltage. In the next figure, it can be seen the different curves of the AIC common mode voltages and the amplitude spectra with and without CM filters:

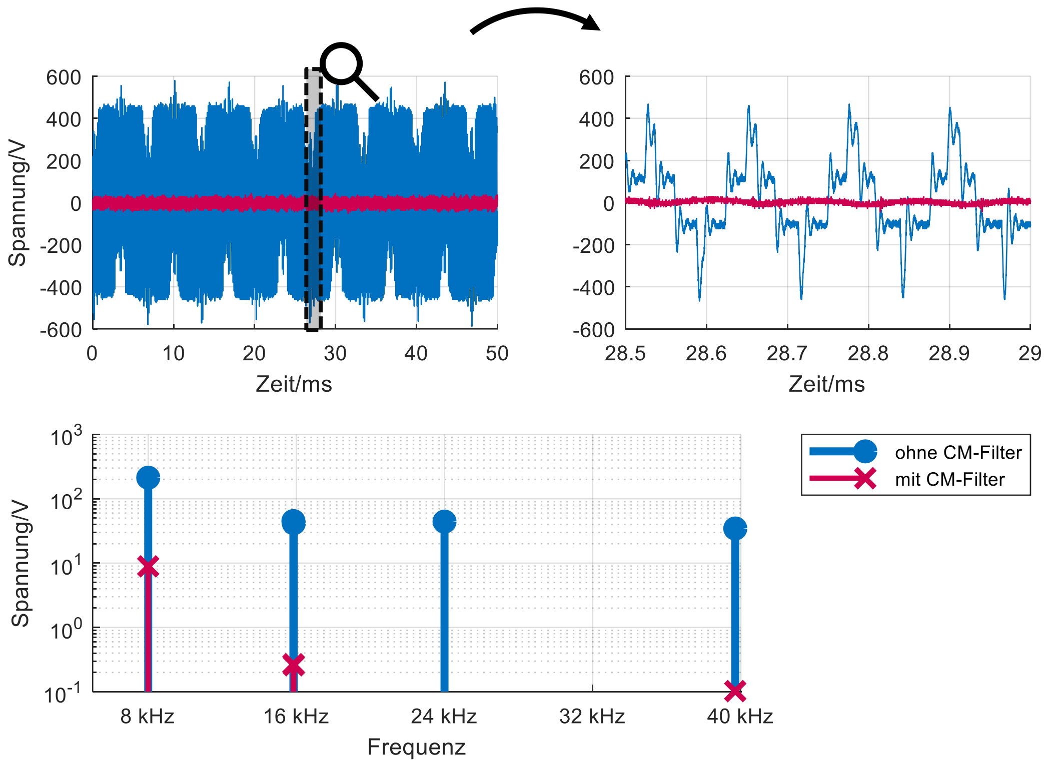


Figure 25: Common mode voltages of AIC with and without CM filters (DC-INDUSTRIE2, 2023)

The designing of the CM filter will give an end to the designing of the AIC, making the device with some more added features another important DC sector of the system. As all of the DC sectors have been defined already, in the next section the arrangement of the DC sectors will be discussed.

5.5 DC Sectors

In this section the concept of DC sector will be explained and the DC sectors that form a DC Microgrid will be defined and arranged. The hierarchy levels that the DC sectors have internally, following a bee hierarchy system will also be explained as well as some rules that should be followed when arranging and connecting the different sectors.

A DC sector is a group of several DC devices which are directly connected to each other by the power flow and are switched and protected together via a DC feeder. With this arrangement, all devices within a DC sector form a logical and functional unit which is disconnected together from the DC grid in the event of a fault. A short-circuit fault within a composite device can lead to the loss of function of other composite devices of the same DC sector but does not affect the continued operation of other DC sectors. Henceforth, sufficiently fast protective devices must be used in the DC feeders. This will be later discussed in depth on point 3.7 Protection and selectivity.

5.5.1 Main DC Sectors

During Phase 3, different elements of the system have been described, and each of them will be forming a DC sector of their own. These are some examples of the types of DC sectors that can be found in a DC Microgrid:

- **AIC:** Stablishes the connection to the AC Gird and forms a DC sector by itself.
- **Energy storage:** Here there can be some debate, as there could exist small storage systems for specific purposes that are introduced in different DC sectors, and they do not form a sector by itself.
- **Energy producer:** The renewable energy power source will compose another DC sector by itself.
- **Production cells or machine group**: Machines and robots supplied by DC.
- **Variable speed drives:** Group of drives that fulfill a special function together.
- **Passive loads:** Lighting and ventilation systems are examples of these passive loads.
- **AC regular sockets:** Used to connect any kind of equipment such as computers, lamps, and other smaller machines.
- **Auxiliary power supplies:** Auxiliary power supply devices are used to generate voltages from the AC or DC grid that are not assigned to the main power flow. There are some clear examples, such as the 24 V supply needed for controllers, contactors or even the PV modules; or the 230V AC needed to supply the electricity sockets. On the next figure, an example of different variants of these power supplies is shown:

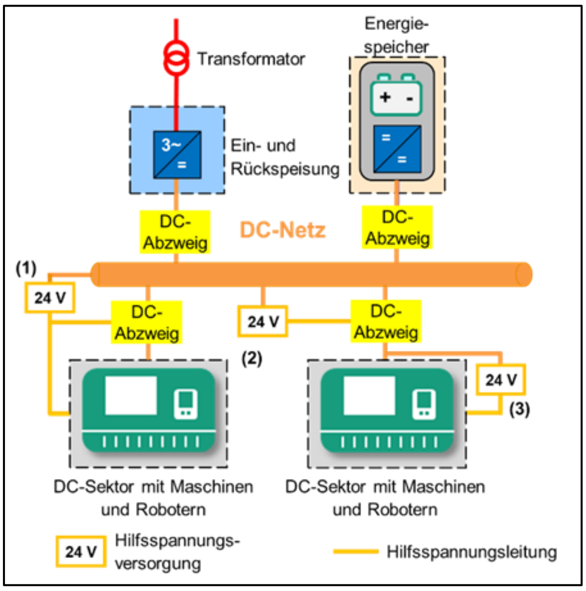


Figure 26: Example of different variants of auxiliary power supplies

There will be two main types: central and decentralized auxiliary power supply devices. The central device will generate the necessary auxiliary voltage (e.g., DC 24V) for the entire system o production cell. Its input is directly from the DC main grid, as it can be seen on the figure above which shows variant number 1. On the other hand, the decentralized type refers to the devices that provide auxiliary power to devices such as inverters, controllers, contactors, …. In this context, decentralized means that the power supply only provides a small part of the required auxiliary power for the entire system at the exact location where it is needed. This means that components such as DC feeders or control cabinets for robots each have their own auxiliary power supply. This is shown as variant (2) or (3) in the figure above.

Once the DC Sectors are defined, a DC Sector sketch will be shown, so that the reader can see a main view of how a DC Microgrid looks like:

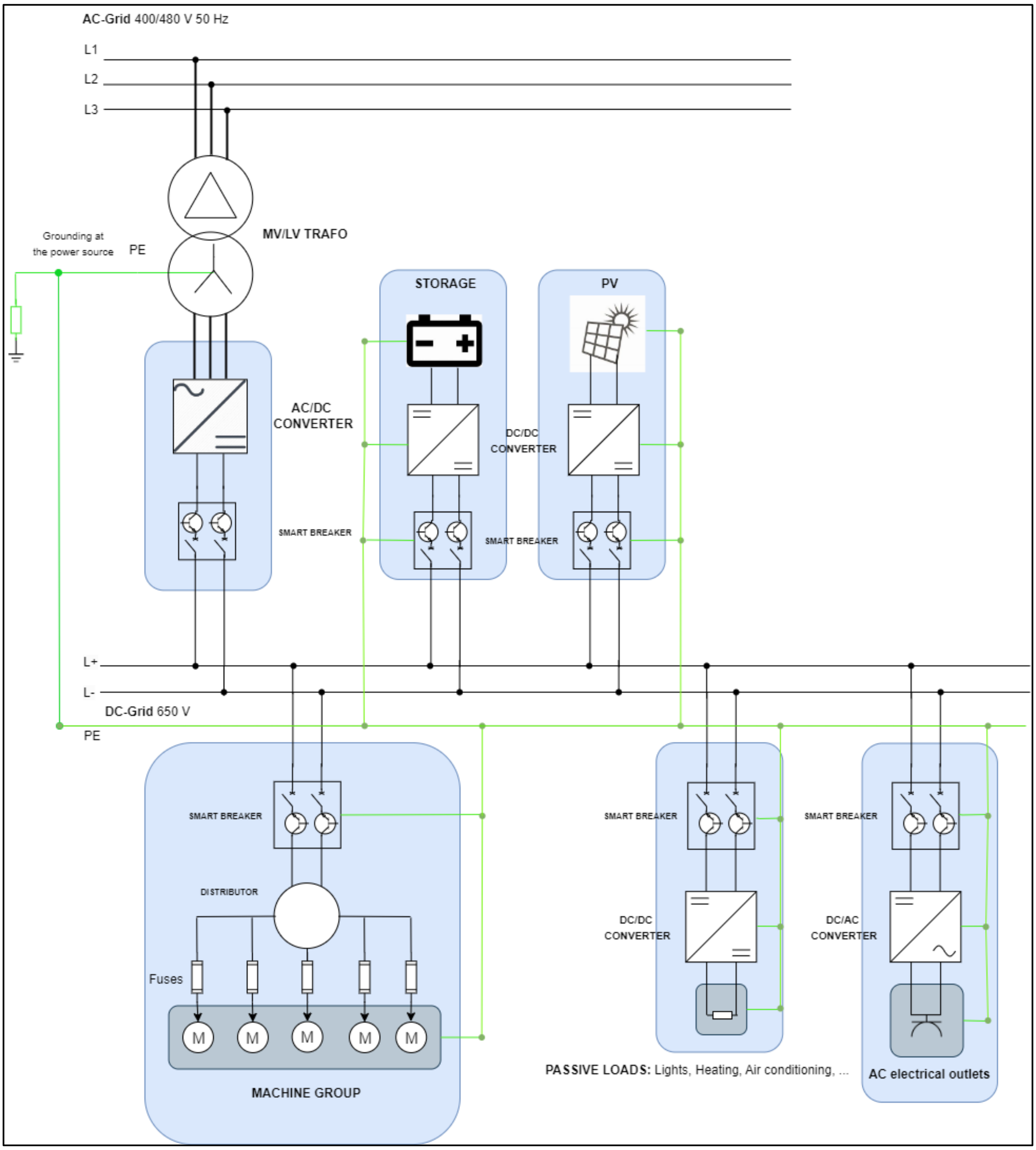


Figure 27: Example of diagram of DC Sectors of a possible DC Microgrid

In the figure above there is a clear example of how a DC Microgrid divided in DC sectors (Blue boxes) will look like. This is just an example of how it can look like. There are other type of DC Microgrids that could have a different number of DC Sectors. It is also important to highlight that inside this DC sectors, more DC sectors can exist as it will be discussed in the next point.

5.5.2 Hierarchy levels

When organizing the different DC Sectors, is important to follow a logic order. To achieve that, the DC Sectors will be given a hierarchy level value, having two different hierarchy levels: 1 and 2. Also, the structure of the DC grid will be divided into three levels that will depend on the current carrying capacity:

- High ampacity
- Mid ampacity
- Low ampacity

In the next figure it can be seen a perfect example of the different levels of current carrying capacity and the two levels of hierarchy regarding the DC sectors:

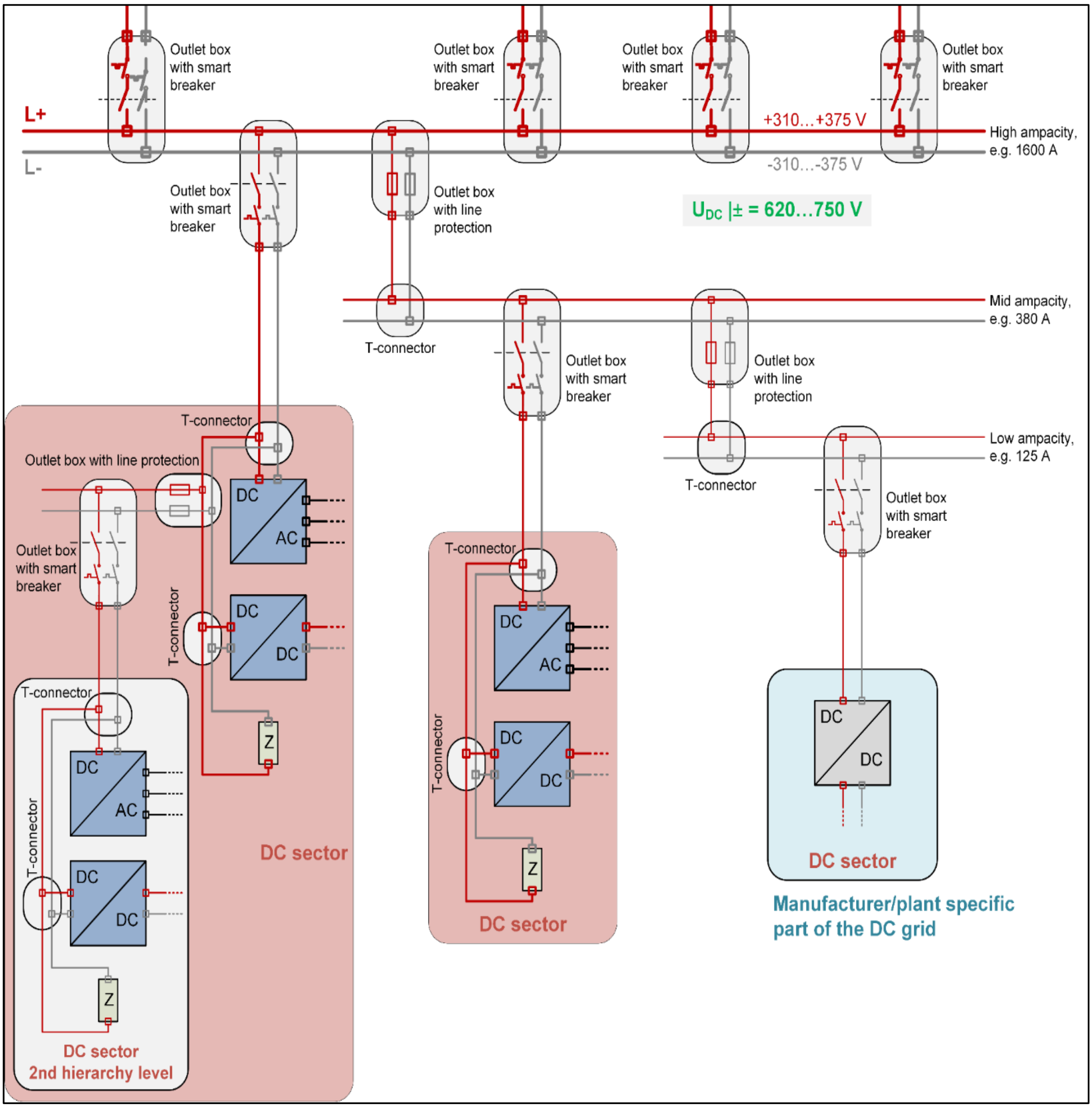


Figure 28: Diagram of DC Microgrid with division of DC sectors and levels of current carrying capacity (DC-INDUSTRIE2, 2023)

In the figure above, the three different current capacity carrying DC buses can be perfectly distinguished, each of them supplying power to the corresponding DC sectors and devices. Also, it is easy to distinguish the two hierarchy levels of DC sectors, being the second hierarchy the lowest level and the first, the highest.

Once the hierarchy levels of the DC sectors are explained and the DC Microgrid´s main sketch realized, it will be time to go into detail with other topics such as the cabling of the system and the protection needed for it.

5.6 Cabling concept and cable protection

In this section, the topic of cabling for the DC Microgrid will be tackled. The design of the cabling system will be overviewed, taking into account the cable protection needed for it and a brief comparison of DC and AC cabling will be done.

The correct design of the cabling system within a DC Microgrid plays an important role as the cabling system ensures reliable power transmission, minimizes losses and brings safety to the system. The main key considerations for an effective design will be the following ones:

- Voltage and current requirements
- Cable sizing calculations
- Selection of suitable cables
- Designing connection points
- Compliance with standards
- Integration of protection devices (will be done in the next section)

First, all the voltage levels of the DC Microgrid should be identified and have different types of cables ready for all the possible levels. These levels can vary from 24 V to 700 V depending on if they are for auxiliary power devices or the main DC bus. Once the voltages are defined, the calculating the maximum expected current capacity, which for the robots and machine cells can be obtained from the 3.1 Phase for example.

Once voltage and current are known, the calculations for a correct cable sizing which will ensure minimal voltage drop and power losses will be necessary. For these calculations, length, temperature, and maximum voltage drop will be necessary.

The next step will be to select the cable type. In this section, the DC cables show how they have different characteristics than AC, so the choice will be a little different taking factors into consideration such as skin effect, voltage drop and power losses. The material will most of the time be Copper but there could also be aluminum conductors.

Another important aspect will be the connection points. The design of the connection points where the different components of the Microgrid will need to be easily accessible for maintenance and troubleshooting in case of a malfunction.

After the design, it will be important to check and ensure that the cabling system complies with relevant electrical codes and standards. It should adhere to safety regulations and guidelines in order to minimize electrical hazards.

Other considerations such as modularity and expandability, labeling, and documentation, testing and commissioning, monitoring and maintenance and environmental considerations will be taken into account too.

A comparison between the DC cables and AC cables will be made now in order to show what advantages could the DC cabling system offer. For the sake of comparing them, an example of an AC motor of 10 kW will be given:

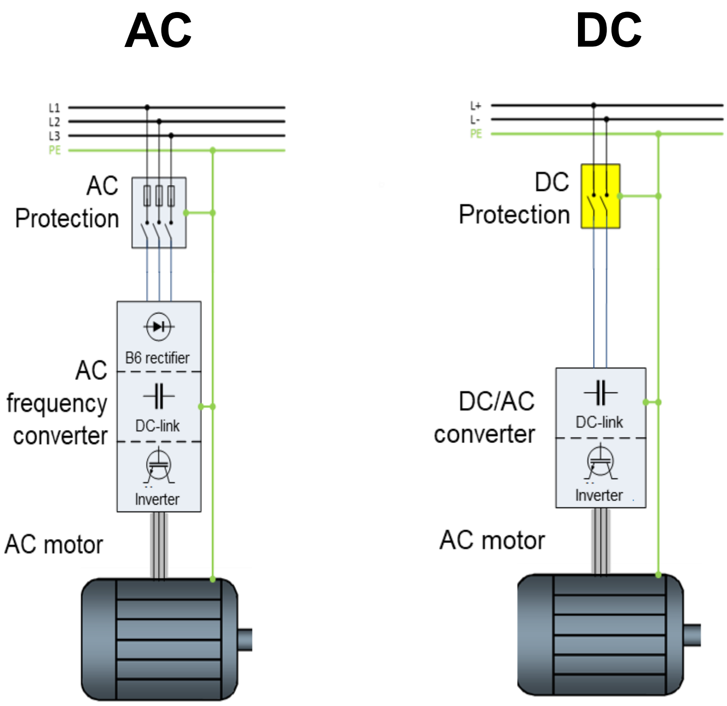


Figure 29: AC and DC connection to AC motor from grid

As it can be seen on the picture above, with the AC grid, because of the need of a Variable frequency drive, a rectifier is needed which will have an efficiency and will have a total power factor lower than for the DC grid, which does not need this rectifier.

Taking into account the next values and equations, a quick calculation of the needed current for each case can be calculated with the next equations:

$$S = \frac{P_{el}}{\lambda}$$

$$P_{el} = \frac{P_{Motor}}{\eta}$$

$$P_{DC} = S$$

$$I_{\mathrm{DC}} = \frac{P_{DC}}{U_{DC}}$$

$$I_{AC} = \frac{S}{\sqrt{3} \cdot U}$$

Figure 30: Equations for the calculation of current for Motor

Where:

- S: apparent power
- λ: Total power factor
- η: efficiency of inverter and motor
- P_{Motor}: Power of motor
- P_{el}: Electrical power

- U_{DC}: Voltage of DC system
- U: Voltage of AC system
- I_{DC}: Current for DC system
- I_{AC}: Current for AC system

From the known values:

- P_{Motor}= 10 kW
- U_{DC}= 620 V
- U= 400 V
- λ=1 (DC) & λ=0.65 (DC)
- H= 0.98*0.85=0.83

Making the necessary calculations with the values from above, the obtained currents are:

- I_{AC}= 26.75 A
- I_{DC}=19.43 A

Once the current has been obtained, taking into account standards from DIN VDE 0298-4) the cross section of the used conductor will be calculated:

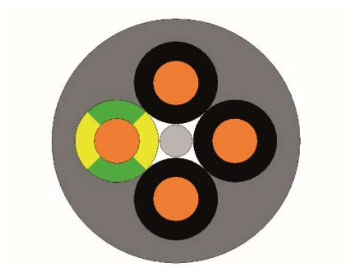
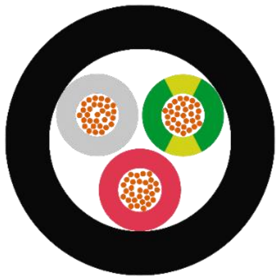
	AC	**DC**
Grid current	I_{AC}= 26.75 A	I_{DC}=19.43 A
Cross section shape	 Four wires (3 Phase conductors)	 Three wires (2 Phase conductors)
Cross section according to DIN VDE 0298-4	4 mm²	2.5 mm²
Total copper	4×4 mm²=**16 mm²**	3×2.5 mm²= $\mathbf{7.5}$ **mm²**
Specific electrical resistance copper	*r* = 0,018 (Ωmm²)/m @ 30°C	
Power loss in cables:	$P_{V,AC,l} = 3 \cdot \frac{r}{A} \cdot I^2$ $= \mathbf{9.66\ W/m}$	$P_{V,DC,l} = 2 \cdot \frac{r}{A} \cdot I^2$ $=$ **5.44 W/m**

Figure 31: Table of comparison between cables for AC and DC

From the table of the figure above, there are two key values that need to be analyzed and compared, the total copper used for the cable and the possible power loss in each of them:

Total Cooper: $\frac{(16-7.5)}{16} \times 100 = 53.13\%$

Regarding the material used, with a DC grid, in this case there is more than a 50% savings in copper, making it much more profitable than AC cabling.

Power loss: $\frac{(9.66-5.44)}{9.66} \times 100 = 43.69\%$

On the topic of power loss reduction, there exists a difference between power loss of a 43.68%, making the DC grid more efficient and reliable than the AC. After this comparison of cabling characteristics between AC and DC and the designing of the cabling is done, the next step will be to give a short explanation of the material used for protection on the cables.

Regarding the insulation of the cables, on the DC industry community, some tests have been carried out to the usual AC cables with the following materials: PVC, polyethylene, polypropylene, thermoplastic elastomers, and halogen-free PO-based mixtures. These experiments included 2500 hours of constant voltage of 1kV and temperatures reaching the 70 °C. (DC-INDUSTRIE2, 2023)

Based on the results of the experiments, these cables tested positively to DC voltage resistance, making them a good choice as insulation materials for the DC grid cabling. However, there was discovered a considerable influence of the ambient medium on the cable. While most of this cabling will be inside of the facility, in case that there was an outside cabling installation, parameters such as humidity from precipitation should be taken into consideration. Regarding the rest of the installations, the materials previously mentioned will be a good choice.

On this section, only the insulation of the cables will be covered, because the rest of the protection concept will be tackled in the next section.

5.7 Protection and selectivity

On this phase, the protection of the system and the possible selectivity needed for it will be discussed. The appropriate devices for each application will be selected, making use of different varieties depending on the level of protection needed for that part of the system. The use of the tools MATLAB and Simulink will help in running some simulations to determine the selectivity of the system.

The protection system is still a topic of discussion in the DC industry community. In this project, the focus will be on giving the possible solutions and explaining the pros and cons that they offer. Before discussing the possible faults that can happen on the system, a table with the characteristics of the possible protection devices will be shown. This table has a very general view, and it only has an indicative purpose for these devices, but it will work as a baseline to make decisions of.

PROTECTION DEVICES	SWITCH	FUSE	HYBRID BREAKER	SMARTBREAKER
SHORT CIRCUIT PROTECTION	O	☑	☑☑	☑☑
OVERVOLTAGE PROTECTION	O	O	☑	☑
OVERCURRENT PROTECTION	☑	O	☑☑	☑☑
SURGE PROTECTION	O	O	☑	☑
ELECTRICAL ARC	O	O	☑	☑
GALVANIC ISOLATION	☑	O	☑	☑
RESPONSE TIME	Slow	Medium	Fast	Super fast

BREAKING CAPACITY	Bad	Good	Ver good	Very good
SELECTIVITY	Impossible	Hard	Easy	Very easy
CYCLES	200	1	ENDLESS	ENDLESS
PRICE	Medium	Low	High	High

Figure 32: Table with characteristics of protection devices

As it can be seen, the smart breakers and hybrid breakers offer solutions for mostly all of the different fault types, but their price is an important factor to take into consideration. Sometimes it may be smarter and more affordable to just use normal switches or fuses.

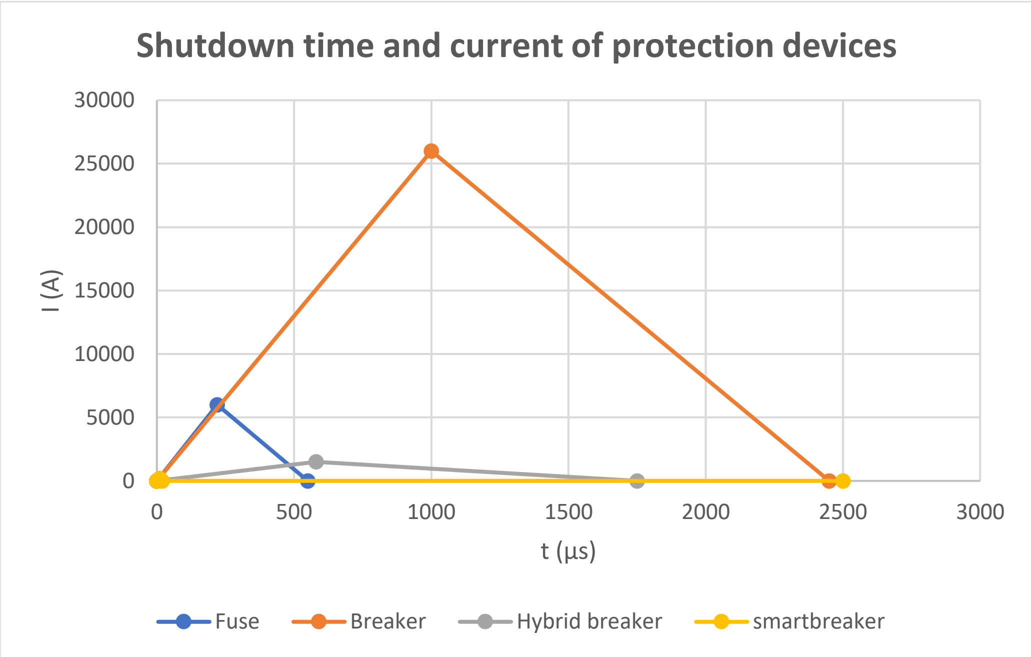


Figure 33: Graph of shutdown time for different protection devices

In the figure above, the time of and current they need to reach in order to shutdown is shown. For the smart breaker´s time and current, it cannot be seen because of the small measure. In the next figure, there is a zooming of it:

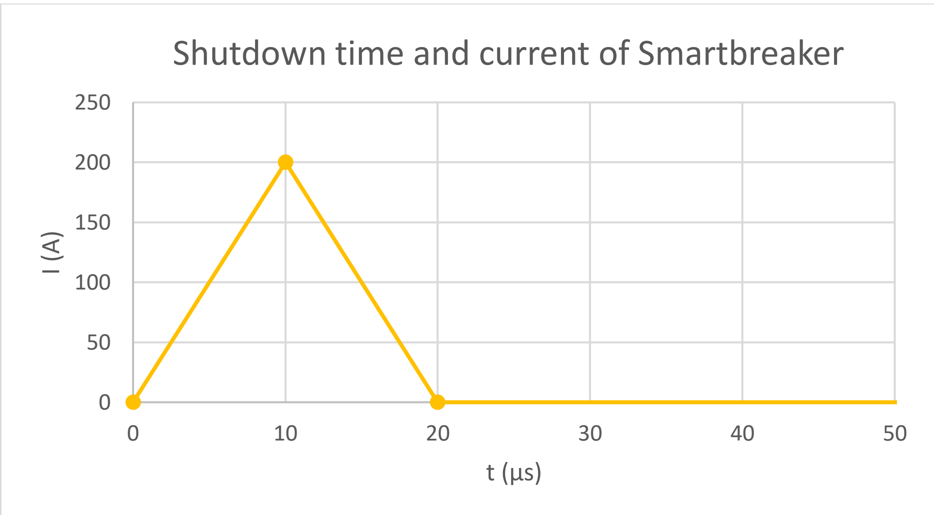


Figure 34: Zoom of the previous figure to the smart breaker area

Now that the characteristics of the 4 possible devices have been set, the different possible faults will be analyzed and the best options for the solving of them shown.

Regarding the overcurrent protection, when an **earth fault** occurs, the type of grounding system will have an impact on the protection devices that will be needed for the system. For a DC system with **AC-side grounding**, fast **protective devices** must be arranged in **both poles** as protection in the event of an earth fault. The tripping characteristics of the fast circuit breakers must be such that they protect the supply unit from destruction in the event of an earth fault. Furthermore, it must be ensured that the supply unit can also deliver the necessary short-circuit current to cause the circuit breaker to trip.

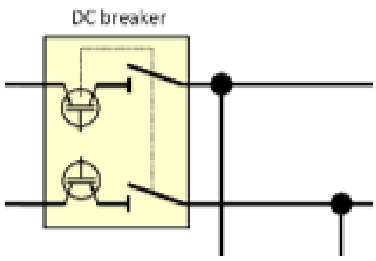


Figure 35: Protection device for AC-side grounding system

Regarding the IT variant, the galvanic isolation simplifies the parallel connection of several suppliers and fast short-circuit protection is **only necessary in one** of the two active conductors. However, a **switching element** must still be provided in all active conductors for the isolation function and line protection.

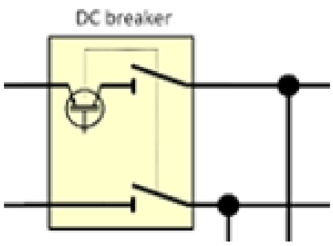


Figure 36: Protection device for IT grounding system

The protection device that would work better in the case of an earth fault could be **fuses** but the best options will still be the **hybrid breakers** and **smart breakers**.

In the event of a **short circuit**, as DC grids are highly capacitive, the fault current in the DC grid increases very quickly. Very fast overcurrent protection devices are therefore required for short-circuit protection. These devices are advantageous due to their fast reaction; they switch off the short-circuit current so quickly that impairments in parallel sectors are effectively avoided. For this case, common fuses may not be able to be fast enough, and they would need to be switched every time a fault occurs. **Hybrid breakers** would be the better and safer choice, as well as smart breakers.

When the protection of the devices of the system refers to **overload**, it is necessary that the tripping behavior of the protective devices is matched to the permissible i^2t values of the devices. Particular attention must be paid to diodes and IGBTs in the supply devices. Device protection can be ensured by current measurement and an i^2t model which could be obtained with **adaptive fuses** or **smart breakers**.

Another different view will need to be taken in case of an **overvoltage**. Overvoltage is a short-term (transient) voltage increases in the time range from nanoseconds to a few milliseconds, which are several times the operating voltage and therefore endanger the insulation of electrical devices and systems. If no protective measures are taken, flashovers within the system or breakdowns of the insulation can occur.

Transient overvoltage can be reliably limited using **surge protection devices (SPDs**). These are designed to limit very short ($t \leq 1$ ms) but very high transient overvoltages. When such a transient overvoltage occurs, the SPD becomes low-resistance and equalizes the potential between active conductors and PE.

When talking about the protection concept, there is a phenomenon that also needs to be addressed: the **serial arcs**. The light arc occurs when a high voltage current jumps across a gap between two conductive materials, for example in the event of an earth fault or short circuit parallel to the load, a light arc could occur between the two conductors with different potential.

The one that should worry and can give problems to the system is the serial arc. It can occur, for example, if a conductor core breaks or if connectors are loose. It acts as an additional load in series with the existing installation and is not recognized by the usual line protection without further measures.

Protection devices for detecting serial arcs are available: arc fault detection devices. These devices work with spectral analysis methods. Industrial DC grids are characterized by a high number of power electronic devices that emit interference in the relevant frequency range, which can lead to false detections, making them not suitable for this purpose.

Furthermore, it is advisable to take increased passive protective measures to prevent corresponding serial faults in mobile electrical components and connections or those at risk from cable pull or breakage. Other kind of protections such as protection against electric shock or corrosion will need to be taken into consideration when designing the protection concept but will not be tackled in this project.

Finally, to finish with the protection concept of the system, the topic of **selectivity** of the system will be explained. Selectivity is the ability of a system to switch off only the directly affected part of the system in the event of a fault in order to ensure continued operation of the fault-free parts and DC sectors as far as possible. Due to the directly parallel-connected capacities in a DC grid, ensuring selectivity is more challenging than in a traditional linear structure with a central generator, as in the event of a fault all storage units attempt to discharge into the fault location.

To ensure selectivity, it must therefore be ensured that the circuit breakers of these unaffected DC sectors do not trip when a fault current is fed from storage devices in their sector into the fault branch. In a selective system, the circuit breakers in the next higher hierarchy levels must not trip in the event of a short circuit in a subordinate DC sector. In the event of a short circuit on the DC busbar, all circuit breakers of the DC sectors that can feed energy into the fault switch off. This usually affects all DC sectors due to the DC link capacitors.

On this topic, the full power load of the DC sectors and the distribution of the loads inside of them play a big role on selectivity. In order to determine, which could be the best possible distribution of the loads, in order to favor selectivity, some simulations with the help of MATLAB and Simulink will be done.

From the results of the simulations, regarding the total load of the DC sectors it has been always determined that if selectivity is needed, the DC sectors should have around the same loads, not going above the 20% of the total power of the system. This will be taking into account that the protection devices would be fuses. As having all the DC sectors being of similar value is really difficult due to logistic reasons, the use of smart breakers becomes more necessary because common fuses will not guarantee selectivity.

On the other hand, for the loads inside of the DC sectors, there are more variables to take into account. It depends on the size of the loads that are inside of these sectors and each case should be analyzed individually. It is very difficult to obtain selectivity inside the sector with just fuses, as when a fault occurs on a large load, the rest of the fuses will also be damaged, making the DC sector useless.

Analyzing the results, it can be determined that in case of the client to demand selectivity, the only possible solution may be the use of smart breakers for the most important and large loads and having a detailed analysis including simulation, in order to determine if for smaller loads the use of fuses could be possible, dimensioning them the right way.

There will be some figures on the appendix regarding the simulation process, so that the reader can have a general idea of how the simulations were carried out. After discussing selectivity, this section comes to an end, opening a path to the last part of Phase 3: Grid functions and operational management.

5.8 Grid functions and operational management

In this section, a small introduction about the management of the DC Microgrid and the control system of it will be given. It is a considerable broad theme, so in this project it will be tried to keep it to the general aspects and not dig further.

DC grid management is part of a hierarchical control process within an industrial production system. Basic control processes, such as production planning and production management influence the functions of DC network management. The control processes are in turn influenced by the DC network management. This can be seen in the next figure:

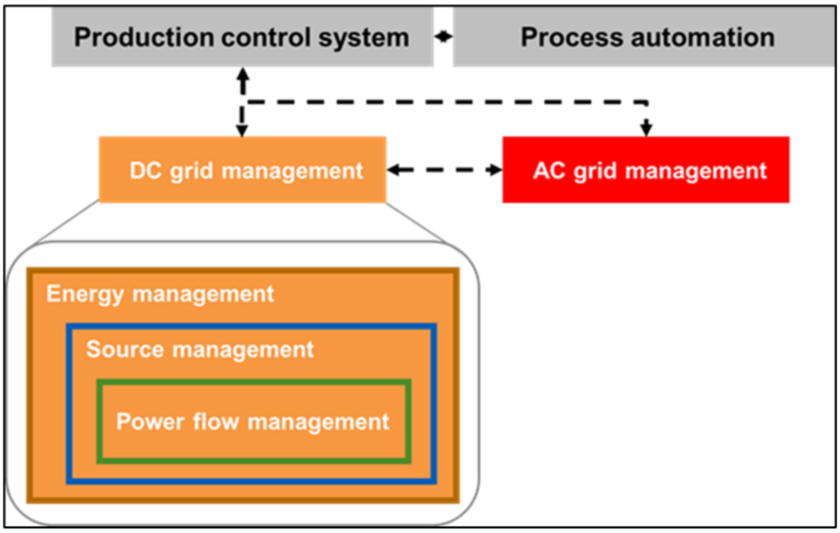


Figure 37: DC network management (DC-INDUSTRIE2, 2023)

As seen in the figure, DC grid management will have a hierarchical level in which **energy management** will have the biggest role in it. It will pursue goals such as reducing energy costs, increasing self-consumption of local generation and marketing energy flexibility.

These goals are pursued considering local and external influential factors. Local factors involve the possible energy demand of the process or the state of the production system. External factors involve factors such as the weather and forecast, the AC main grid fluctuations or production schedules because of market demand.

In the second hierarchy level, inside of the energy management, the **source management** could be found. It is in charge of transferring the energy management measures to the sources, which are the mainly the principal participants of the DC grid. These sources will provide controllable power and will be influenced via a control system.

On the third hierarchy level, will be the communication infrastructure between the energy management and source management. The **power flow management** will regulate the provision of power from the sources and will be responsible for ensuring that the power is balanced. In order to keep an stable operation of the grid, the grid voltage will need to be kept within defined limits. This will be achieved through different expansion stages of power flow management. There are a total of 4 possible choices:

- **Basic network:** Decentralized power flow management. No control. No communication
- **Decentralized group control:** Decentralized power flow management. With control. No communication
- **Extended group:** Decentralized power flow management. With control. With communication control
- **Central network control:** Central control system that sends setpoints to all devices

The one that be mostly used will be the extended group which consists in a decentralized power flow management system with control and communication, making it the perfect option for having an efficient system.

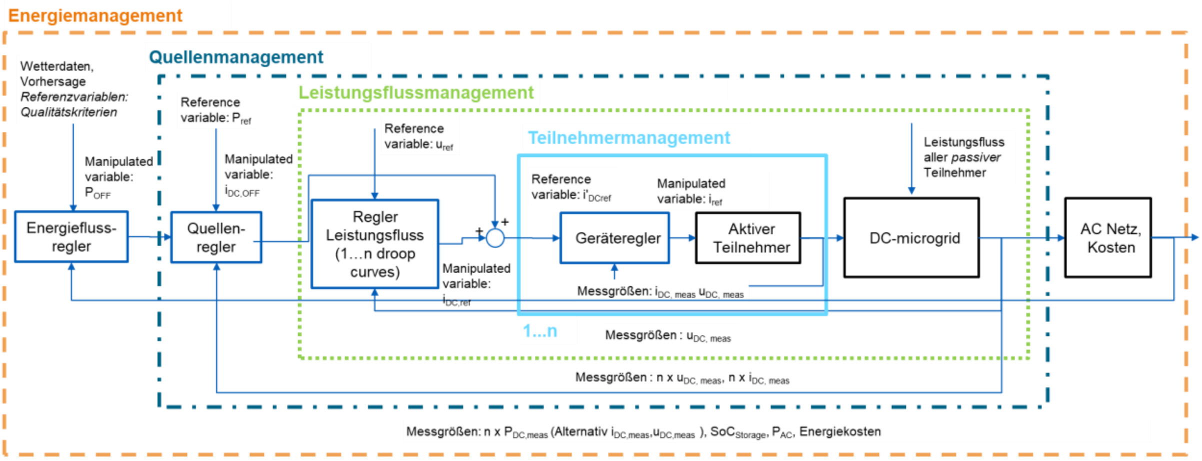


Figure 38: Example of the decentralized control system with communication (DC-INDUSTRIE2, 2023)

The basis in an actively controlled DC grid is the voltage-controlled regulation of the current, which will be achieved by the use of **droop curves**. The communication medium is the grid voltage, which is a measure of the balance between power demand and power supply; in other words, the voltage increases when there is excess power and decreases when there is insufficient power. Source management affects the controllers in the active devices via a current offset that shifts the control characteristic.

The concept of the droop curves is to control the power flow, for example to ensure the parallel operation of supply devices and storage units in a decentralized control system. The procedure must be implemented in all active supply devices and energy storage units for group control. All devices are current-controlled and the setpoint value of the current is determined with a characteristic curve from the current DC mains voltage U_{DC}.

The control characteristics for active devices define the relationship between U_{DC} and i_{DC}. U_{DC} is the DC grid voltage at the terminals of the device. The load counting arrow system applies, i.e. the current i_{DC} is positive when the current flows into the device from the DC grid (sink mode) and negative when it flows out of the device (source mode). On the next figure it can be seen how a droop curve looks like and the modes of the device, depending on the current and voltage:

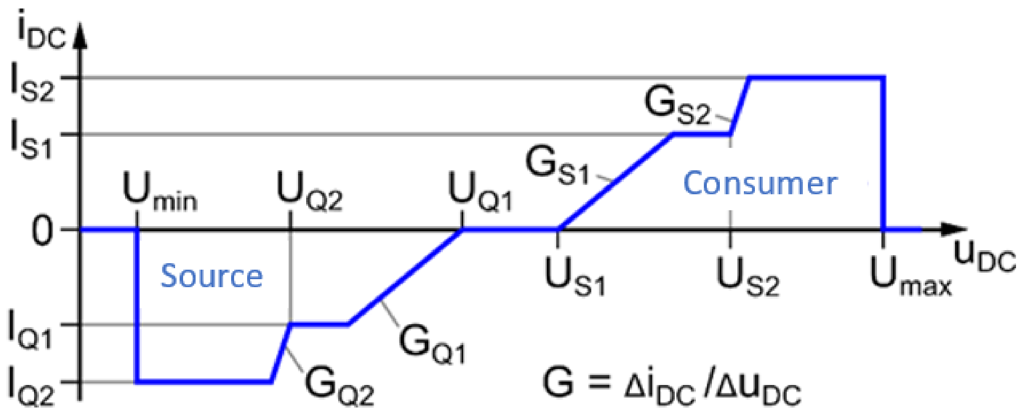


Figure 39: Overview of typical droop curve

Once the droop curves are explained, this section will bring to an end the last subphase of phase 3, finishing the explanation of the process of the designing and modelling of a DC grid. Next section will include a real case in other to materialize all this information and help the reader to grasp the utility of this process.

6. REAL CASE APPLICATION

Once all the phases of the project have been explained and described, the best way to show how it would work is to apply a real case in which the process previously described is followed and later analyze the results obtained from it for future possible improvements or remarks.

For this section of the project, a middle-sized industrial site on the automotive sector from Germany will be presented. On this case, the user will be in need of designing a factory which already has some previous AC infrastructure but wants to introduce a DC Microgrid to expand it. One of the main reasons why they are interested in this DC Microgrid is to obtain a CO_2 neutral production process and save energetic costs while doing it.

Here are some of the main characteristics of the project:

- Automotive sector
- Important role of PV power
- Important role of Energy storage
- AC transformer
- Good grid stability
- German regulations for grid standards (DE)

Once some of the main goals of the user are defined, the first step will be to bring out the questionnaire and obtain the information necessary in order to start with this project.

6.1 Phase 1

On this section the questionnaire already filled out with the answers will be shown and later some small comments will be added in order to open a path to the second phase, which will make use of this information.

6.1.1 Local set up

Existing Infrastructure

Which type of grounding should be used?

DC grid with AC grounding.

Are there specific existing AC or DC connection points?

Yes, connected AC side that is already there and also will be used.

Are there any existing power rails/cables to be used?

Only on the AC side.

Is there an existing decentralized power generation to be integrated? (e. g. PV, CHP)

PV 500 kW already installed.

If PV is present: Is there an energy profile?

No.

Is there already energy storage to be used (e. g. battery)

Yes, a battery of 350 kWh.

Location

What is the location of the power supply inside the factory?

It will be right next to the main building.

What distance exists from the power supply to the loads?

Depends on which loads as there will be a lot of different machines.

What distance exists from the power supply to the transformer?

Approximately 200 meters.

What distance exists from the transformer to the PV, Batteries, …?

It will depend as there are different sites for PV and batteries.

Cooling

What cooling options for components are required/available/allowed?

There will be around 12 ventilation devices.

Sound

Are there noise limit values?

Keep the noise limit to a value where the workers are able to work comfortably.

PV-Regulations

If necessary, which PV regulations in DE, EU or international should be considered?

German regulations (DE).

AC-Grid-Country

How high is AC voltage, AC frequency? (400V/50Hz, 480V/60Hz, ...)

400 V 50 Hz.

How good is the current grid stability/quality?

Good quality and stability.

Are there specific standards/guidelines to be observed?

Not at the moment.

AC-Grid-EVU (electricity and energy suppliers)

Are there any limitations to the continuous performance?

No.

Is there a maximum permissible peak performance?

Try to keep peaks to the minimum.

If applicable, what is the allowable return power?

Around 500 kW.

Are there particularly high or low energy prices to be considered?

No.

Is there a data connection to the EVU? (e. g. smart grid)

No, but there is a plan of having one.

AC-Grid-Factory

Is there a medium or low voltage distribution in the factory?

Yes.

Are there any restrictions on the permissible medium/low voltage power for the installation?

No.

Is there a separate transformer for the DC grid?

No, both DC and AC will be supported with the same transformer.

6.1.2 User requirements

Load

How high is the sum power requirement and what should be used in the DC area (e. g. light, air conditioning, . . . list of devices)?

70 machines, total load of around 4 MW (Later division in next phase).

Is a simultaneity factor considered?

0.7.

Producer

Is a high-performance local energy supply planned for self-sufficiency, CO_2 reduction or island grid operation? (e. g. PV, CHP, battery)

Yes, PV.

If yes: should the network be operated autonomously (black start)?

Maybe.

Back feeding / Usage of the grid

Should regenerative energy be fed back into the AC grid?

Yes.

Should the system be operating grid friendly?

Yes.

Storage / Grid quality

Should a balancing of power peaks or a reduction of the connection power be implemented?

Yes, power peak reduction.

Are there grid errors or outages that need to be bridged?

Not that we know of.

Producer / Supplier

Are there components or sub-systems that need to be designed redundantly or otherwise protected against failures?

Not that we know of.

Connection / Supplier

Should power reserves be planned in order to be able to expand the plant successively in the future?

Not really.

Priority of application

Are there any production processes that need to be prioritized?

Yes.

Selectivity

Can one part of the system fail if a short circuit occurs in another part of the system?

Yes, but it should try to keep the process running.

Wanted control system

Which control of the system is desired? (Decentralized control, decentralized control with communication, centralized control)

According to DC industry rules (Decentralized control with communication).

From the questionnaire answers, there are some key points that can be highlighted:

- There is already AC infrastructure installed
- DC will play a big role in this factory
- Back and forth relationship with the AC main grid will be needed
- Large energy storage for power peaks and grid stability
- Large PV power supply
- Very effective protection

This information will prove crucial for the next phase, making it the baseline for the decision-making process of Phase 2 and clarifying aspects such as the grounding system that will be used, the PV needed to be installed or the power supply topology to connect with the AC main grid.

6.2 Phase 2

For phase 2, like previously explained, the grounding concept will be defined as well as the link to the AC main grid, an energy analysis will be made, and two options of possible designs will be prepared for the user in the shape of brief sketch of the schematic configuration of the system.

6.2.1 AC link and grounding

Starting with the grid interface of the DC system, from the information obtained from the Phase 1, there will be a transformer station that will be shared with AC systems, which will also supply power to the DC Microgrid. The input voltage will be of **400 V and frequency of 50 Hz**.

Taking a look at the answers from the questions related to the relation of the DC Microgrid with the AC main grid, it is clear that bidirectionality will be necessary as the user demands for the possibility of feeding back power to the main grid. For this reason, the bidirectional power supply with voltage regulation will be selected: **Active Infeed Converter**.

Regarding the grounding concept, with the previously options discussed in this document and the answers of the user, the DC Microgrid will be using **AC-side grounding on TN-C-S system**, as it is the most simple and smart solution, taking into account that there already exists a previous AC grid.

6.2.2 Energy analysis

The next step will be the energy analysis, which will involve obtaining the total power consumption dividing the known loads of the system into different groups, defining the power sources and describing a way of optimizing the energy used by the system.

In order to obtain the total power consumption, a table with all the loads that there is a knowledge of should be filled:

MAIN LOADS (Machines)		PASSIVE LOADS		OTHERS		
Name	Power(kW)	Name	Power (Kw)	Name	Power (Kw)	
Stamping presses (x15)	15×40=600	Cooling system	1500	DC outlets	150	
Welding machine (x10)	10×35=350	Heating system	1100	Other equipment	300	
CNC machines (x5)	10×30=150	Lighting	500			
Painting lines (x5)	10×20=100					
Robots (x10)	10×35=350					
Assembly line (x5)	10×20=100					
						TOTAL POWER (kW)
	1650		2000 or 1600		450	**4100**

Figure 40: Table with loads of the system

From the table above, the **total power requirement** for the system can be deduced to be: **4.1 MW**. Regarding the cooling and heating system, only the one with the highest power be taken into consideration as only one of them will be on while operating, in this case, is the cooling system.

Analyzing the value of 4.1 MW of total power required, it makes sense as it is on the power range of what a mid-size industrial site that focuses on the production of doors and other complements on the automotive sector. Now, once the power load is known, the design of the power sources will be handled.

The power sources of this DC Microgrid will be the main AC grid, the renewable energy source (which will be PV) and the energy storage system.

Main AC grid:

The first source of power will be the main AC grid and the value of the obtained power from it cannot be lower than 4.1 MW. To be on the safe side, in case of any problem, a AIC of 4.5 MW could be installed, or two in parallel of 2.25 MW. This option will probably be more costly, but it could make the grid more flexible, ending up in a smart investment. Both options will be given to the user.

Renewable energy source:

As mentioned before, the renewable energy source will be PV modules. There is already 500 kW installed, and by the user´s request, the PV capacity will be increased. As the objective of the user is to depend on the renewable energies greatly, a large capacity of PV will be installed. Installing an extra batch of PV modules, between 600 kW and 1 MW, some of them being on the side of the installation while others will be absorbing energy from the rooftop of the factory.

This would make the total PV capacity to increase greatly. With this much capacity and with the help of a corresponding energy storage system, a large portion of the total power load will be covered. It will be a significant investment at first, but taking into account that the location has good conditions regarding solar irradiance and the need of it, it will end up being a good investment.

Energy storage system:

In order to be able to make the PV system work efficiently, a large energy storage system will be needed too. There are some requirements from the user in Phase 1 such as peak power reduction, the possibility of a black star system, giving power back to the AC main grid and being grid friendly.

In this case, there will also be two possible options. One will cover most of the wanted specifics and the other will fulfill the main aspects of the requirements.

For the first option, as there is a large consumption related to the heating and cooling systems as well as the lighting, there will be a thermal energy storage with a very large buffer storage. This will allow to use the energy surplus that is generated and make good use of it.

Also, a mid-sized battery will be installed, which will take care of reduction of power peaks and will be working in synchronization with the PV in order to give power to the main system when needed. With this energy storage, the user has reassurance that most of the necessities of the industrial site will be covered in case of a malfunction or fault on the main AC grid.

The second option, being more affordable, will include the mid-sized battery, which will help greatly to the system's efficient use of the PV power source. There can also be installed some supercapacitors next to specific machines of the system which have certain power peaks, allowing them to be corrected. In order to do this, there should be some energy profiles regarding these power peaks, so that the correct design of the ultracapacitors is carried out.

As there is not a lot of information about the energy profiles of the machines involved in the system, there is not a lot of optimization to be done regarding the storage system apart from aligning it with the PV power source and making it charge with the surplus of energy generated by it on peak hours and using this storage power during hours of low solar energy production or peak price from AC main grid, in order to save energy costs.

6.2.3 Schematic configuration

On this last step from phase 2, two different sketches will be shown to the user, corresponding to two systems which will be very similar in structure but will have different characteristics taking into account the budget of the project and the path that the user wants to follow. In the next two figures, these sketches with their corresponding characteristics tables are shown:

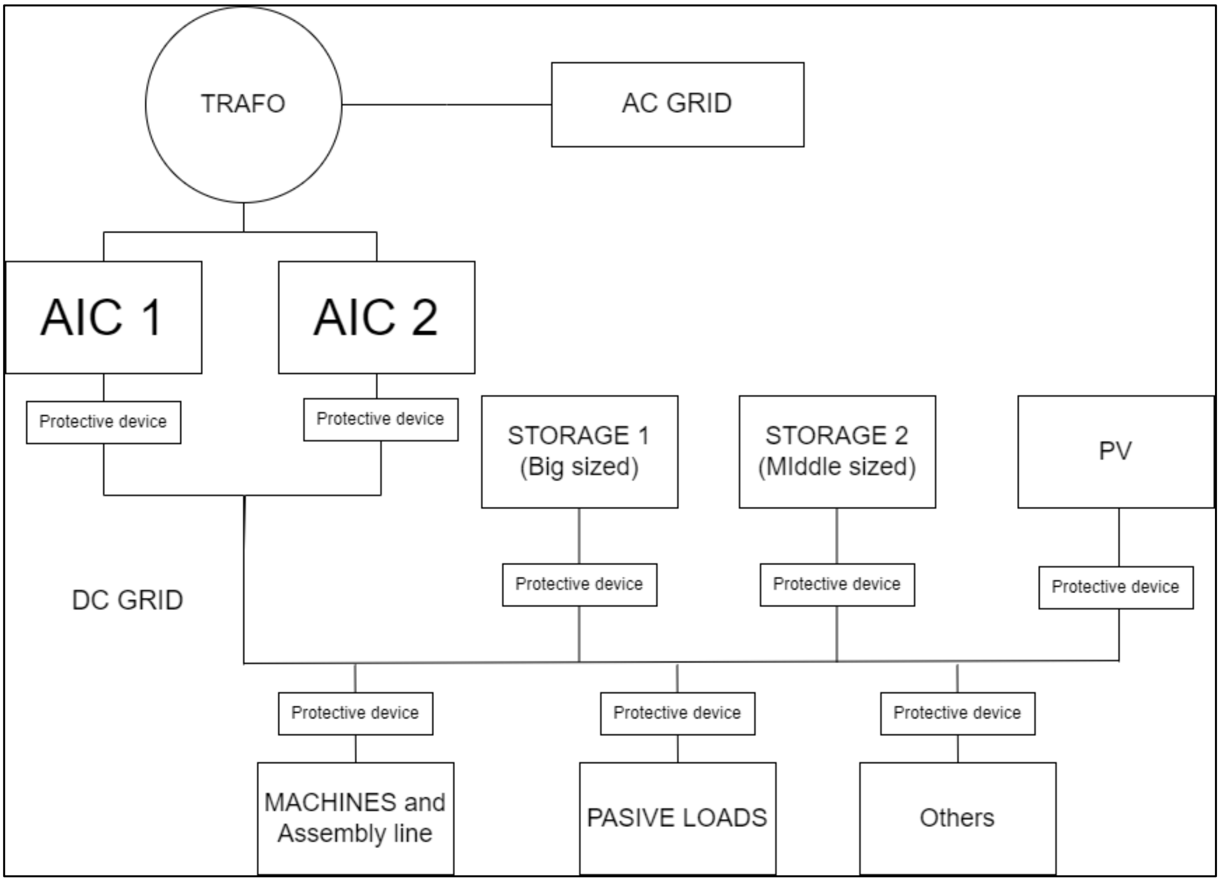


Figure 41: Sketch of option 1

The sketch above will be a system with the following characteristics:

Main characteristics	
Elements	**Information**
Budget	High
AIC	Two AIC of 2.25 MW
Storage	Combination of large sized storage and mid-sized storage
PV	Old: 500 kW + New: 500kW-1MW
Protection	Full protection (Smart breakers)

Figure 42: Table of characteristics for option 1

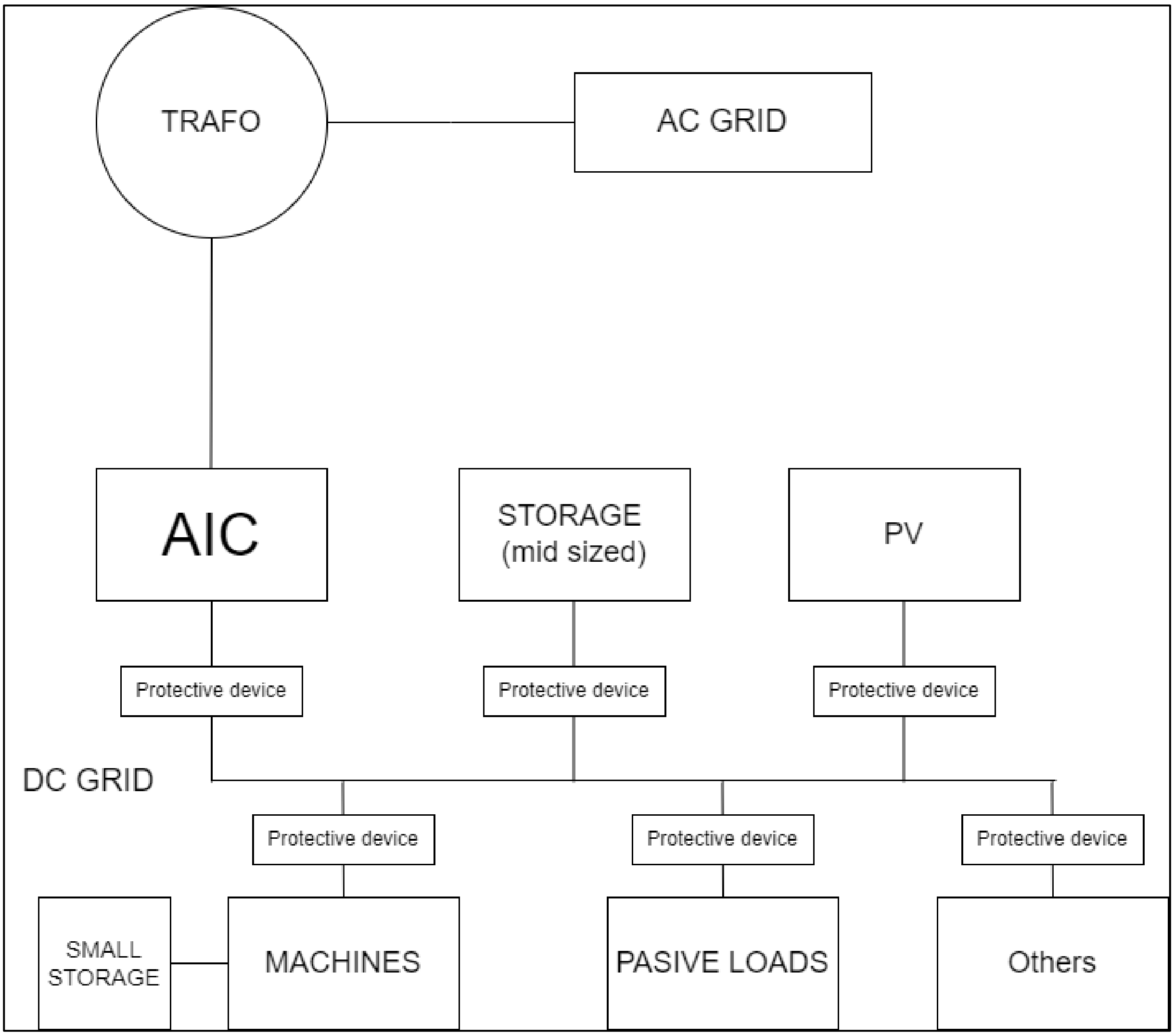


Figure 43: Sketch of option 2

Main characteristics	
Elements	**Information**
Budget	Medium
AIC	AIC of 4.5 MW
Storage	Mid-sized storage and small sized storage for power peaks of machines
PV	Old: 500 kW + New: 500kW-1 MW
Protection	Normal protection (Smart breakers, common breakers and fuses)

Figure 44: Table of characteristics for option 2

After careful consideration and regarding the pros and cons of the choices presented, the user will decide to follow the path of the **first option**, making the designing of the DC industry more complete and improving the efficiency of the system, as well as the possible functions.

6.3 Phase 3

After phase 2 and already defining the path that will follow this project, on Phase 3, the points regarding more explicit designing and modelling will be covered. Before jumping on it, the questionnaire regarding this phase will be filled in order to obtain the necessary information:

Energy consumer

How many loads does the system have?

The system has around 80 loads, counting all of them.

What is the nominal power of each of them?

It will be shown in the next point.

What is the load factor of each of them?

It will be shown in the next point.

Is there any energy profile for each of them?

There are for some specific machines.

Are there any special specifications of the machine or the drives individually that should be known?

Not right now.

Energy producer

Is it possible to integrate new decentralized energy? If yes, which should be the target value?

Yes, the target to be reached should be around 1,4 MW.

Will there be power fed to the AC grid?

Yes.

Energy storage

What time frame should be aimed for?

At least 5 minutes.

Active Infeed Converter

Is there any plan of expansion in the future?

Not at the moment.

Is redundancy needed?

Not really.

DC Sectors

What dependance exists between the loads?

There is dependance between the loads of the production system, will be explained in the next point.

Is there a cluster of loads?

Yes, 1 assembly line, 1 painting line, 2 robots and 1 CNC machine center makes a cluster of loads.

Cables and cable protection

Is there any floor plan?

Not at the moment.

What will be the ambient temperature of the industrial site?

25 °C.

Protection and selectivity

Are short circuits or overload faults occurring?

Not frequently.

Is selectivity a must? If yes, is it needed for all the system?

The more selective the system the better, at least for the main production.

Grid functions and operational management

Is energy management needed?

Yes.

Is power management needed?

If possible, yes.

Should we aim for AC-grid support? If yes, what kind of support?

Yes, give back power to the AC grid and be grid friendly.

Once the questionnaire is finished, the consumers will be analyzed. There are some questions´ answers which have not been fully recorded here because they are too long and they will be shown in the next phases, such as the list of loads and the nominal power of them.

6.3.1 Consumer

In this section, a table with all the loads and the characteristics from it will be shown. The next figure will divide the different auxiliary and main devices into production cells and groups with a code explained in section 5.1.

Name of the load	Production cell	Dependendy group	Load group	Installed Power (kW)	Load profile	Voltage (V)	Load factor	Current (A)	Average Power (kW)	Average Current (A)	Code for the load
Stamping press (x15)	1	B	a	40	LP	700	0,8	61,54	32	49,23076923	B.1.a.40.LP
Welding machine (x10)	1	B	a	35	LP	700	0,8	53,85	28	43,07692308	B.1.a.35.LP
CNC machine center (x5)	2	A	a	30	-	700	0,7	46,15	21	32,30769231	A.2.a.30.-
Painting line (x5)	2	A	a	20	-	700	0,75	30,77	15	23,07692308	A.2.a.20.-
Robot (x10)	2	A	a	35	-	700	0,68	53,85	23,8	36,61538462	A.2.a.35.-
Assembly line (x5)	2	A	a	20	-	700	0,74	30,77	14,8	22,76923077	A.2.a.20.-
Vents (x12)	3	C	b	50	-	700	0,8	76,92	40	61,53846154	C.3.b.50.-
lights (x100)	5	C	b	5	-	700	0,9	7,69	4,5	6,923076923	C.5.b.5.-
AC outlets (x100)	5	B	b	1,5	-	700	0,7	2,31	1,05	1,615384615	B.5.b.1,5.-
Reversible pumps (x3)	3	C	b	200	-	700	0,72	307,69	144	221,5384615	C.3.b.200.-
Water heat pump	4	D	b	210	-	700	0,8	323,08	168	258,4615385	D.4.b.210.-
Water tank	4	D	b	90	-	700	0,7	138,46	63	96,92307692	D.4.b.90.-
Circulating air heater	3	C	b	300	-	700	0,8	461,54	240	369,2307692	C.3.b.300.-

Figure 45: Table of loads of the system

In order to understand better the system, an explanation of the main production system will be given. There will be two big groups, one including the stamping presses and welding machines, and the other the assembly line with their corresponding machines working on it.

There will be five assembly lines which will include 1 CNC machine center, 1 painting line and two robots each. In this way, 5 cluster of loads will form in this group, while the rest of them can have more freedom and do not depend so much on the rest of the system.

Once all the loads of the system are counted for and divided into different groups, it will be the turn of designing the energy producer, the PV.

6.3.2 Energy producer

Regarding the energy producer, previous work has been done deciding the approximate value of the total power that will be needed and wanted from the PV modules.

Looking at the questionnaire from phase 3 and checking the previous phases it has been decided to install a new PV system of 900 kW peak total. This will be divided in two locations. The rooftop of the factory will hold modules with 300 kW peak capacity, while the other 600 kW will be installed next to the industrial site.

While now the new installation will have 1.4 MW power peak of PV capacity, other factors will be taken into account to obtain the total possible power that can be delivered out of the system. In order to make an estimation, solar data from the area (Bavaria) should be analyzed.

In order to have an optimal estimation, the best course of action would be to contact an expert on this area, but for the sake of simplicity the next values will be used obtained from a reliable source:

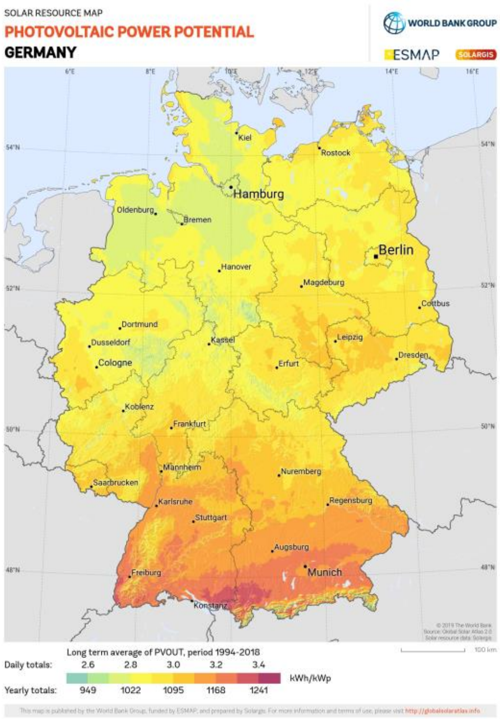


Figure 46: Map of the photovoltaic power potential in Germany (Solargis: Maps and gis data, 2019)

As it can be seen in the figure above, the photovoltaic power potential in the region of Bavaria has been very large during the years, making it an excellent zone to make use of the PV energy. From the scale, an estimation of 3.3 kWh/kWp of power potential can be assumed.

Making an easy calculation with the 1,4 MW power peak at disposal, the approximate value of power that can be obtained in a day from the PV modules will be of: 4.62 MWh. Although this value is just a rough approximation and many more factors need to be taken into consideration in order to obtain a more precise value, it will help to understand the capacity that the PV system has to supply the industrial site.

From the previous estimation, it can be determined that the PV installed will be a large source of energy for the system and could reduce by a large margin, the dependance of the system on the AC main grid. In order to achieve this, the energy storage will also have a big role.

6.3.3 Storage

To make good use of the PV system from the previous section, the storage should be designed accordingly. The task will be to define how many storage systems, how large will their capacity be and what role can they fulfill. From phase 2, it has been determined that there will be two main storage systems.

The first will be a mid-sized storage system, which will be a battery of capacity still need to be determined. For the second storage system, the user requires a thermal storage unit with a very large capacity. In this case, a **thermal energy storage** with up to **9 MWh** buffer tank for refrigeration or heating will be planned.

This thermal energy storage can be charged not only with the surplus of energy from the PV source but also it can be designed to absorb the excess of energy in the shape of heat coming from the industrial processes happening on the site.

For the mid-sized battery, some calculations can be made regarding the user requirements. The user asks for the system to keep running for more than 5 minutes. In order to be able for the system to run, at least 3 MW of energy are needed for the main loads and some auxiliary loads. If we aim for 5 minutes:

$$Energy\ (kWh) = Power\ (kW) \times Time\ (h)$$

$$Energy\ (kWh) = 3000kW \times \frac{5}{60}(h) = 250kWh$$

In order to keep the industrial process working without stop for at least 5 minutes, the energy storage needs to be of at least 250 kWh. As the system needs at least 250 kWh and the option of not having to shut down anything in case of blackout, a **battery of 350 kWh** will be designed in order to be on the safe side.

Also, the load profile of two types of machines of the process have been given: the stamping presses and the welding machines:

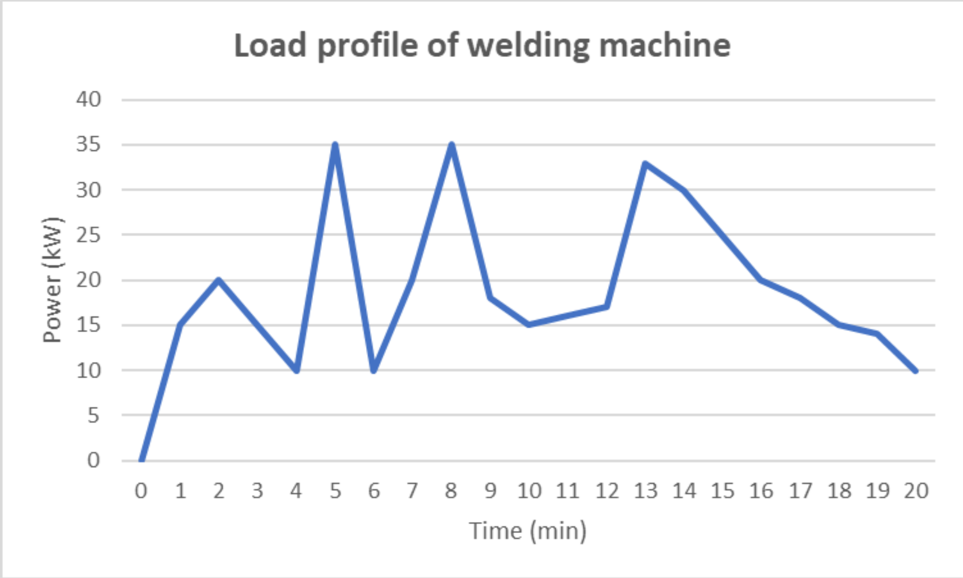


Figure 47: Load profile of welding machine

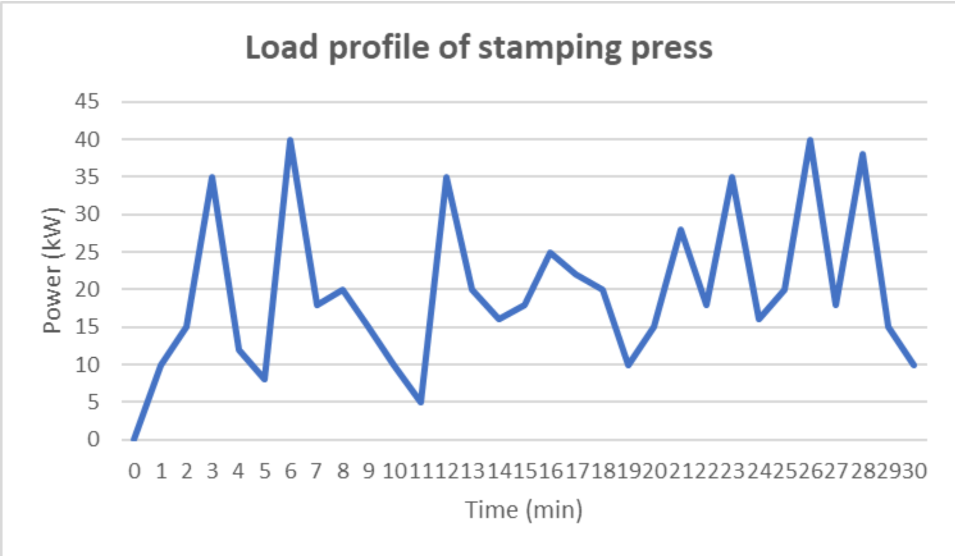


Figure 48: Load profile of stamping press

As it can be seen on the figures above, both of them present some power peaks, specially the one of the stamping presses, which by itself will not make a big impact on the AC grid requirements, but because of the magnitude of having 15 and 10 machines respectively of each of them, it could pose a problem.

It has been decided to design the storage system so that when both of them require more than 20 kW the energy will be supplied by it, having the AC main grid to only supply up to 20 kW during all the time that last the process. This would be the results:

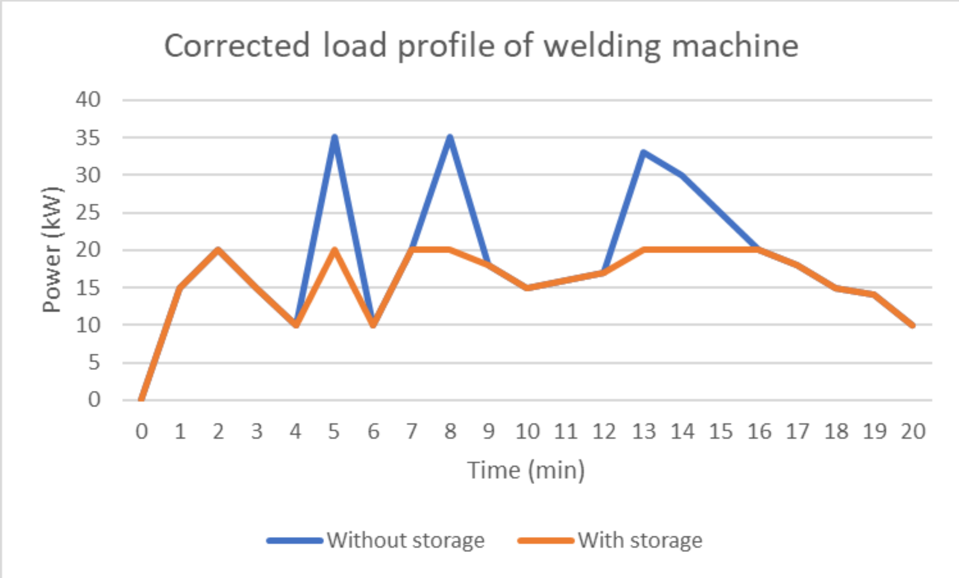


Figure 49: Corrected load profile of welding machine

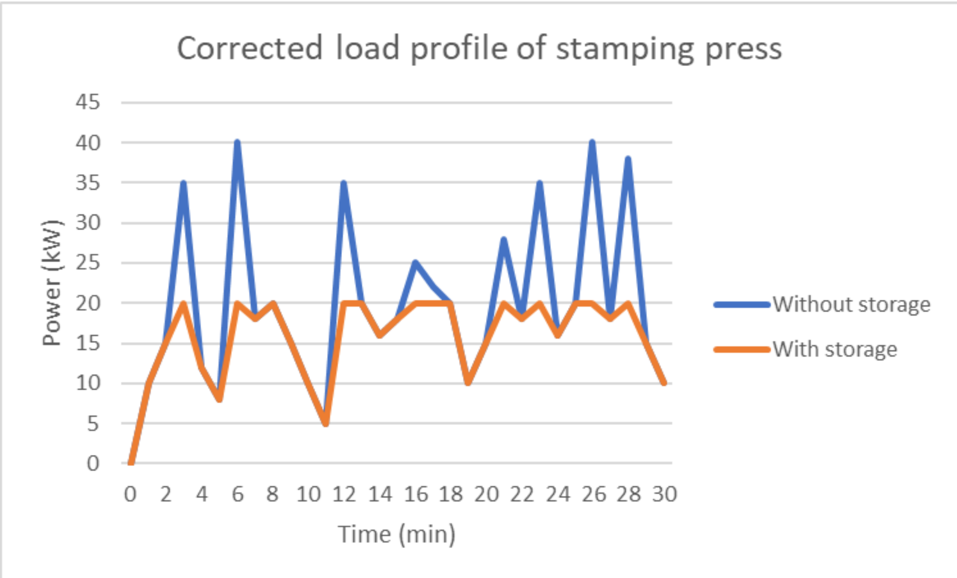


Figure 50: Corrected load profile of stamping press

Although these corrections are small, it could improve the overall efficiency of the system, as the AC main grid will have a constant energy demand, not incurring in extra costs. Having other load profiles of different devices or of the production process will be vital in order to make adjustments and improvements on the DC Microgrid. Once the storage has been defined, the power supply of the system will be discussed.

6.3.4 AIC

For the power supply, it has already been stablished before that it will require the use of an Active Infeed Converter. In this case, the use of two of them in parallel will be proposed. This will give some advantages to the system:

- **Redundancy and reliability:** If one of them encounters a failure or fault, the other can continue running, keeping a proper supply for the system.

- **Scalability and flexibility:** Parallel operation will facilitate the adjustment of power capacity depending on the changing load requirements.
- **Load sharing and balance:** Sharing the load will make them work at a lower load, preventing from being overburdened.
- **Maintenance:** Having two AICs will help with the maintenance operations, as they could take turns in supplying power while the other is getting checked up.
- **Efficiency optimization:** Parallel operation will allow for a better efficiency, as the AICs will be able to operate closer to the optimal efficiency points.

Once the AIC has been decided as the power supply device, the next topic to discuss will be the grid codes. As the industrial site will be located in Germany, it will need to follow the grid codes from this country. The AC main grid in Germany is very stable and reliable in comparison with other countries and the grid codes do allow for the feedback energy to the main grid as auxiliary energy. Although there is a possibility of returning power to the AC main grid, there will be a maximum value for it. Because of the previous installation, the fixed maximum value of return will be of 500 kW.

The next topic to be discussed will be the island grid. In order to be able to have the possibility of the system to work as an island grid (black start), first the DC Microgrid should be equipped with the necessary devices for it.

The first characteristic to take a look at will be the grounding system. IN this case, the grounding system is AC-side grounding, so it is important to have in mind, then once there is a fault on the AC main grid and the DC grid becomes isolated, the grid form will change, working as an isolated DC-IT grid. When the AC main grid is disconnected, short circuit currents could happen, so the system must be prepared, and protection devices installed.

The industrial site could work as an island grid for some time in case of fault in the AC main grid, having the AIC controlling the flow of the power meanwhile and being prepared for a smooth transition when the AC main grid is active again. The time that is able to hold the system on will depend more on the capacity of the energy storage and the renewable energy source. As the production of doors on the automotive sector usually does not require for the process to keep running, this quality is not so important as if the site had an ongoing chemical process.

Finally, the last step to designing the AIC will be to decide on the functions of the filter from the AIC. This situation is special, as there will be two AICs working in parallel so combined factors will need to be taken into consideration.

The choice of having one common filter for both AICs has been chosen as it is more cost effective and because the AICs will have similar characteristics and the requirements for them will be the same. The parallel disposition of the AICs will make the common-mode noise of both converters to combine, needing to design the CM filter to it. The synchronization of both AICs will be crucial in this aspect.

For the type of common mode filter that will be used, a hybrid that combines both inductive, resistive, and capacitive elements will be used, this will give the best results in common-mode noise suppression. For more detailed information, information about the common-mode voltage should be obtained.

To finish with the designing of the filter, the physical layout should be taken into consideration, by paying attention to the placement of the components such as capacitors, inductors, and resistors. Simulation on the performance of the common filter for the parallel AIC system should be made for confirmation that it fulfills the desired specifications.

Although the designing of the AIC requires different proceedings and a very thoughtful process, this project will not dig deeper into it as the objective is to give a general and simple view of the process of designing and modeling a DC Microgrid. Once all the main elements of the Microgrid have been designed, it is time to organize them.

6.3.5 DC Sectors

In this section, a diagram will be shown with all the elements of the DC Microgrid that has been designed from the time being. The objective will be to give an overall view of the system to the user, and it does not mean that the system will end up looking exactly like this.

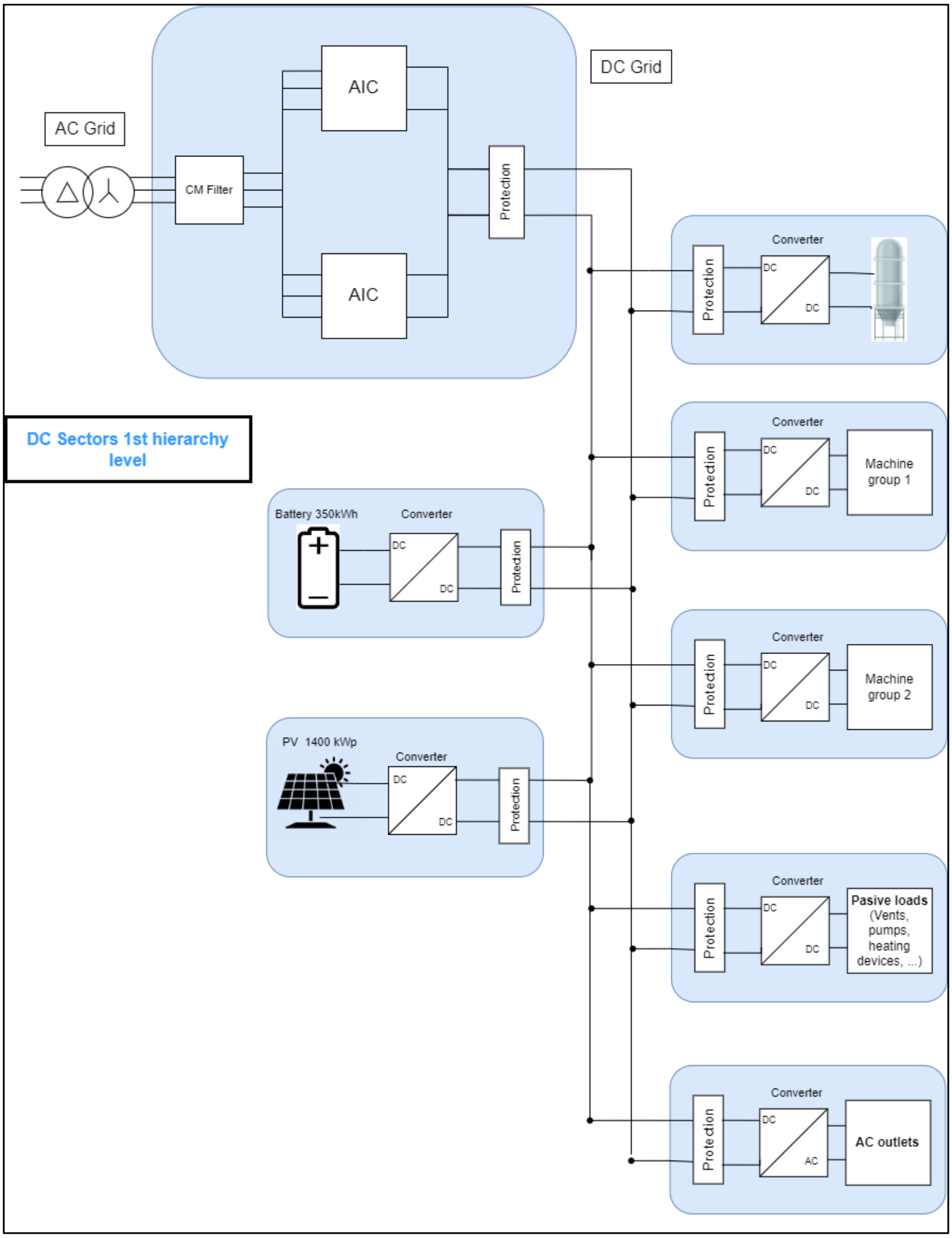


Figure 51: Sketch of DC Sectors

As it can be seen in the figure above, there are a lot of DC Sectors for this special case. It has been decided to divide the storage system into two separate DC sectors, as each will be directed to different tasks. The battery storage will be close to the PV as they will work together. On the other side, the thermal energy storage will be placed on the side of the machines, heat pumps and different auxiliary systems as it could use the extra energy dissipated in the form of energy during the process and have a closer relation with the cooling/heating system, because it will be focused on covering that area.

Regarding the main industrial process of the site, the machines have also been divided into two groups. The first group will include the welding machines and the stamping presses, while the second group will include the rest of the machines which will work as assembly line system. There will also be DC sectors for the AIC, the PV source, the passive loads and the AC outlets and rest of equipment.

In the figure above only the first hierarchy level of DC Sector is shown, but there will be a second hierarchy level which will involve both machine groups:

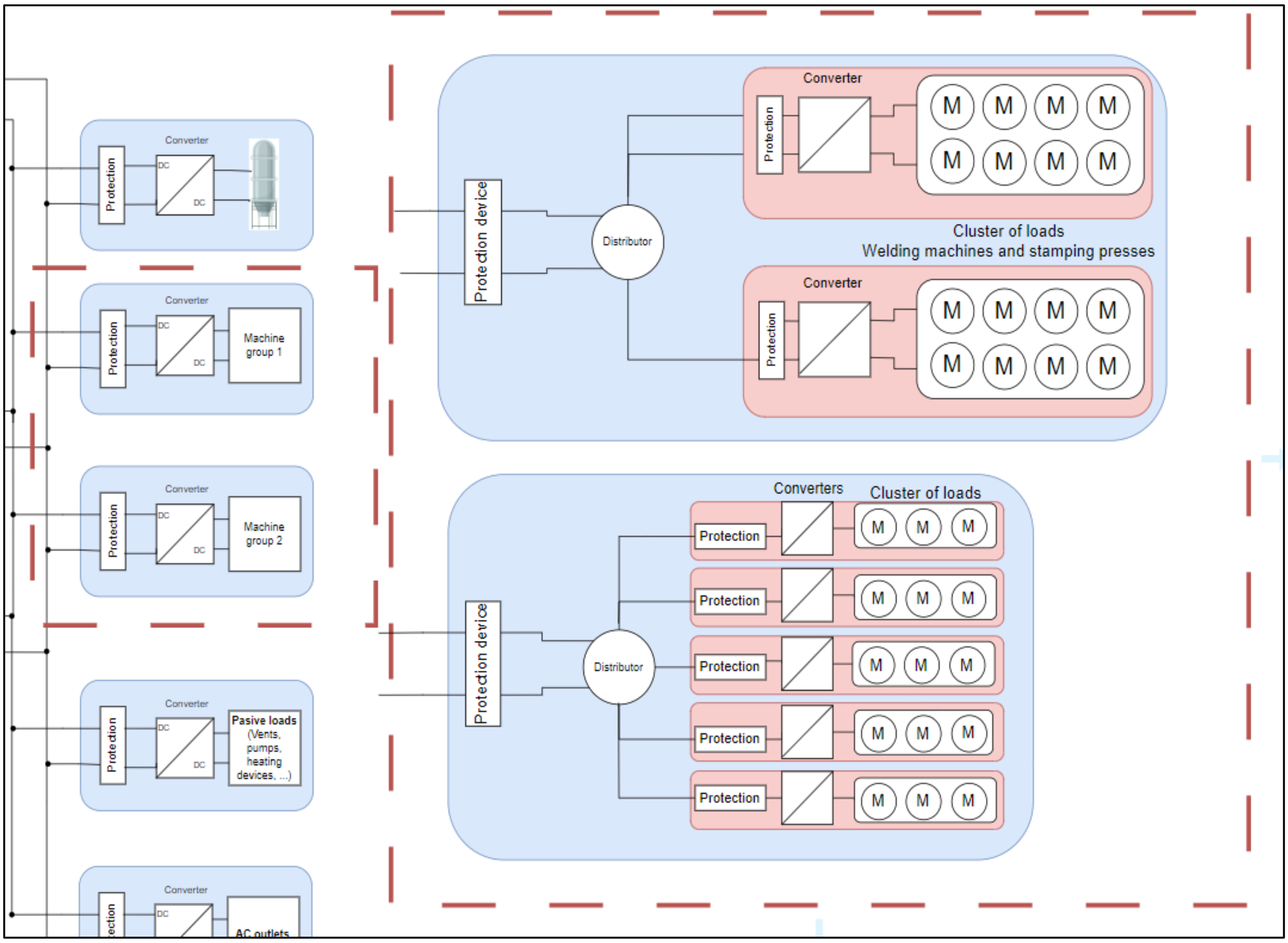


Figure 52: Second hierarchy level sectors

The second hierarchy level DC sectors will help to separate the production process and have a more selective and protective system. For the first machine group, it will be arranged into two DC Sectors, each of them taking care of one each type of the machines. The second machine group will be divided into 5 DC sectors, which will be the 5 assembly lines formed by the machines needed for the industrial process.

Once the DC sectors and the hierarchy levels have been defined, the next step will be to connect all of them, in order to do that, the designing of the cabling concept will be covered.

6.3.6 Cabling concept and cable protection

Regarding the cabling concept, it is not feasible to design all the cables that will be involved on the system, but some of the main aspects can be covered and discussed. A table with the corresponding characteristics that the cables for different application should have will be shown:

CHARACTERISTICS	Length (m)	Current (A)	Voltage (V)	Cross section (cm^2)	Material	Isolation
Main DC BUS	200	1600	700	6,63	Cooper	PVC
Cable for welding machine	15	40	700	0,152	Cooper	PVC
Cable 3	...	...	...	...	Cooper	PVC
Cable 4	...	...	...	...	Cooper	PVC
Cable 5	...	...	...	...	Cooper	PVC

Figure 53: Table with cabling characteristics

On the table above, the main characteristics of each cable will be shown. The current and voltage will be values obtained from phase 3.1 or given by the customer. The current will be the average current, calculated with the load factor given by the user, making the value more reliable than just calculating it with the nominal power of the load.

Having the length of the cable, the current and the voltage, the cross section of the cable can be calculated. When calculating the cross section, the voltage drop needs to be taken into account, as it cannot be too high, otherwise the line could have some problems if the cable is very long.

Finally, the materials used for these cables will mostly be cooper for the conductor and PVC or other similar polymer for the isolation. In this regard, there is not much to be decided as it has previously been seen that the working concept of them will be very similar to the AC cables.

6.3.7 Protection and selectivity

Regarding the protection of the system, the devices that will be used for protection have not been defined yet. In this system, smart breakers, circuit breakers, hybrid breakers and even fuses will be used, depending on the requirements of it.

Before defining the possible protection devices for the system, it is important to take a look at the grounding system. As stated before, the grounding system of the DC Microgrid will be a AC-side grounding TN-C-S type system. This will imply that fast protection devices will need to be installed on both poles as protection in the event of an earth fault. The use of fast **circuit breakers** here is needed in order to protect the supply unit from getting damaged.

For the rest of the devices on the system, it will follow a hierarchical approach, starting with the use of the smart breakers. The smart breakers are the best possible protection device to be installed, having all kind of different functions and fastest reaction time to a fault on the system. This kind of device will only be used on the most important loads as the price of it is very elevated.

On the entrance of the next following DC Sectors, a **smart breaker** will be installed:

- AIC
- Storage system 1
- PV
- Machine group 1

- Machine group 2

The easy and more secure option would be to install a smart breaker at the entrance of all the DC sectors, but doing so, the system would start being less cost effective. This is the main reason why the smart breakers are only installed on the most important DC sectors, which involve power supply to the system and the loads in charge of the main industrial process of the site.

On the second hierarchy level, the **hybrid breakers** will become a great and more affordable solution, which will still offer reassurance on the protection side. These devices will be used on the entry to the rest of the DC sectors:

- Storage system 2
- AC outlets
- Passive loads
- 2 hierarchy DC sectors: At the entrance of the Cluster of loads

For this hierarchy level, still selectivity is desired, that is why hybrid breakers will be used, which will not bring the effectiveness of a smart breaker, but it will be able to keep selectivity when a fault happens.

Finally, **fuses** will also be used in many points, but the most important will be:

- Stamping presses and welding machines
- Each of the assembly lines

In order to keep the fault in one machine to affect the rest, the connections to each of the stamping presses and welding machines will have a fuse, making them selective between them to a certain degree. Also, it helps that the loads are of the same value, helping the selectivity between them as mentioned on a previous point.

Also, there will be a fuse before the group of each assembly line, in order to protect and separate the 5 assembly lines from each other. It will not make too much sense to protect and create selectivity inside the assembly line, because when one of the machines does not work, the rest will not be able to finish the production process, making them useless. For this reason, there will not be fuses connecting to each machine individually in this group.

Many more protection devices will be involved on the system, but they will be handled later. Also, different simulations would need to be done in order to assure the system to work properly. Once this is finished, the next phase will bring a close to the designing and modelling process: the grid functions and operational management.

6.3.8 Grid functions and operational management

This last section will bring a close to the general phase of designing and modelling of this DC grid. It is important that this section is at the end, because although this is an iterative process, where it is possible to jump from phases back and forth, in order to define this one, it is necessary to have all the elements of the system.

The first task of this subphase will be to choose the type of power flow management that the system will be using. Per user´s request and according to the DC Microgrid´s layout, the choice of this will be the **decentralized group with communication and control**.

This kind of control system will be the best option to exploit the energy management of the storage system and PV source working together. A strong connection between them will prove essential for the correct and efficient operation of the system. Also, the communication infrastructure will help to with the fast detection of faults and status of diagnosis. The load peak shaving activity will also be achievable and in an event of communication failure the system will continue operating.

In order to be able to keep up this system, a monitoring system will be a primordial tool. Real-time monitoring, visualization of the grid-configuration, fault monitoring, data acquisition and analysis will be some of the most important functions that will need to fulfill.

On this section, the concept of droop curves (characteristic curves) will play a key role. As it has been stated before, this curves-based control system will be the way of controlling the energy management of the system and deciding how the devices should act depending on the situation.

For example, tone of the most important topics of this case will be the parallel operation of the AICs. In order to limit the common mode currents happening from them, the boundary conditions will need to be observed. Also, suitable control characteristics must be configured so that they can work correctly.

The design of a droop curve will be designed for the next possible situations:

- Both AICs feed power from the grid
- Only one feed energy from the grid
- None feed from or feedback the grid
- Both feed energy back to the grid

This way, a control system of feed in and feedback from the AC main grid will be stablished. In the next figure, the graph representing the droop curve for both working in parallel can be seen:

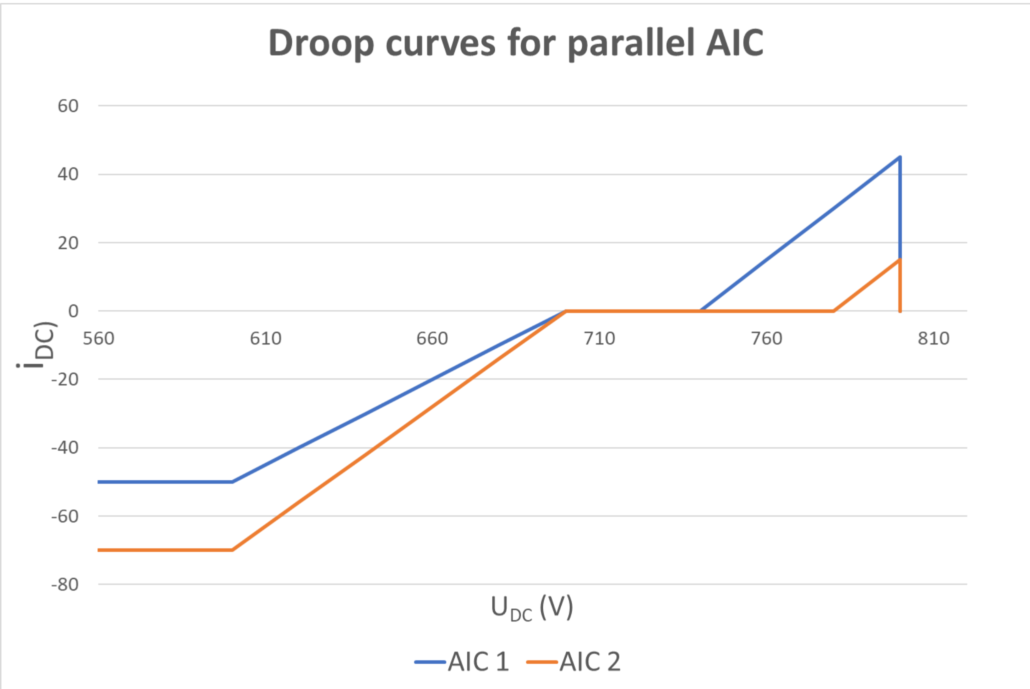


Figure 54: Graph of droop curve for both AICs parallel operation

From the graph above, it can be seen the different working conditions for both of the AICs, when bellow 700 V, the i_{DC} is negative, so they will be working on "source" mode, in order to give power to the DC grid and while the voltage is in reasonable levels, both of them stop supplying power in both directions so that the energy storage can work without any kind of interruption or disturbance (i_{DC}=0). When the voltage starts increasing, at first one of the AIC will switch to "consumer" mode, taking power from the grid and giving it back to the AC grid. If needed, when the voltage gets higher, both will be working together to give power back to the main grid, as it can be seen on the graph. Finally, when the voltage reaches a value of 800 V, which could pose dangerous for the system and not on the range of working conditions, both AICs will shut down.

Once the droop curves have been explained, this last section will close the subphase 3.8, but not finishing the phase. This phase 3 should follow an iterative method in which once all the different points of the designing process have been tackled, another overview of all of them should be made as there will be necessary changes that have appeared during the designing process.

Once an overview of all the subsections is made, the process for designing and modelling of the DC Microgrid will be considered finished giving way to the discussion of the results obtained from this project.

7. RESULTS AND DISCUSSION

After the real case has been finished, the results obtained from this project are clearer and they can be analyzed and discussed. In this section, topics such as the magnitude of this project, the advantages that the DC Microgrid can bring, the biggest challenges of the project and possible future research will be discussed.

Regarding the main objective of the project, the designing and modelling of the DC Microgrid, the creation of a guide which follows a series of fundamental steps proves the best way to fulfill this objective. The complete explanation and adaptation of this guide is done when applied to a Real Case, being able to reach the main goal proposed in this document.

The guide or process to follow can always include more information and be more precise, but it would defeat the purpose of this project. Having a guide of the general process that can be easily followed becomes essential when designing an industrial plan as the main designer will probably not have all the knowledge needed for all the different smaller and precise aspects of the system. This process will enable the first and general steps of the construction of the system, laying the foundations for a later more precise completion.

Nevertheless, the reason as why the DC Microgrid is a viable option and could prove as a better alternative also needs to be present during this project. In the explanation of the phases, it is clearly seen how the implementation of a DC Microgrid, with a proper design, could bring multiple advantages, especially on the topic of renewable energy integration and saving material. Here are some of the main advantages that could be extracted from the analysis:

- **Efficiency:** The efficiency of a DC Microgrid shows an improvement in contrast with the usual grid as there are less energy losses regarding the equipment and the levels of resistance and reactance
- **Renewable energy integration:** The integration of the renewable energy is obviously more efficient as the renewable energy sources usually generate DC power and the DC Microgrid is able to integrate them without additional conversion equipment.
- **Integration with energy storage:** The usage of energy storage, such as batteries, also improves as they usually store energy in the form of DC power. The correct use of these systems in sync with the renewable energy source will bring many advantages to the system.
- **Power quality:** The power quality of the DC system should be better as problems associated with harmonic distortion, voltage sags and other phenomena involving the AC systems are not present.
- **Material costs:** The analysis of the cabling for AC or DC current has already shown that more than 50% of material (copper in this case) is needed for the DC cabling, ending up in significant cost savings.
- **Grid independence:** The “Island Grid” concept allows the DC Microgrid to be able to operate without the need of relying on the AC Main grid, making the system protected against power outages or grid failures.

Although the DC Microgrid does offer a lot of advantages, there are also many additional features that a normal AC system would not have and that need to be taken into consideration. The main problem that is constantly appearing on these systems is the protection concept.

The concept of the DC Microgrid is still new and is a topic that requires a lot of investigation. The protection of this kind of systems can prove essential in order for a industrial process to be efficient. The main problem with it is that the level of protection needed for it sometimes cannot be obtained with conventional fuses or switches, the use of a smart breaker is sometimes needed in order to ensure selectivity. Although there is a constant effort to try to improve and lower the price of these devices, they are too expensive now, making their use not always affordable.

Digging further into the topic of protection, the obtention of selectivity has proven to be also a difficult task. Through Simulink simulations some results regarding selectivity have been obtained and it has been determined that some factors need to be taken into account such as the power capacities of the DC sectors and the devices used to protect them.

Another important aspect of the DC Microgrid would be the control system. It has been determined that the importance of the control system regarding the efficient use of the energy storage system and the renewable energy sources will be crucial for the system to work properly.

The use of the droop curves to determine the way the devices should be working makes the DC system very dependent on the correct functioning of the control system. Therefore, a correct definition and implementation of a control system will end up in a optimal design of the DC Microgrid for an industrial site. As this is explained on the last part of phase 3, it shows the importance that Phase 3 as an iterative method has.

There are many factors to consider during the designing and modelling, and these factors alter each other easily, that is the main reason why this phase should be iterative. For example, during this iteration, the protection system concept could alter the distribution of the DC sectors, making the system more efficient. Also, the order of the phases gains importance in this process, as the definition of the general parts of the system will be done at the beginning and the phases involving all the system will come later, finishing with the control system, which can only be designed once there is a general layout of the complete system.

Finally, because this project has a general view and does not get fixed on specific technical topics, there is some future research that could help to the development of understanding on this project. The two main themes that have not been deeply explored and have a lot of possible investigation are the selectivity problem of the system and the operational management of the grid.

Although some simulations have been made to obtain values regarding selectivity and how to achieve it in a DC system, there are still many simulations that can be executed with different type of systems and power values, in order to obtain some clearer results and conclusions that could be applied to any case. For the time being, this topic only has very specific results for each of the cases.

Regarding the operational management of the grid, the control system and the droop curves are only the superficial part of it. As these systems are relatively new, the designing of control systems for them has proven to be difficult and future research on this topic will prove essential for the future development of the DC Microgrids implementation.

In order to be able to understand how the process of the project has been done and to view the results obtained from it on a more financial point of view, the next section will show a Gantt diagram where the time spent on it will be shown and an economic analysis of the project.

8. GANTT DIAGRAM AND ECONOMICAL ANALYSIS

8.1 Gantt diagram

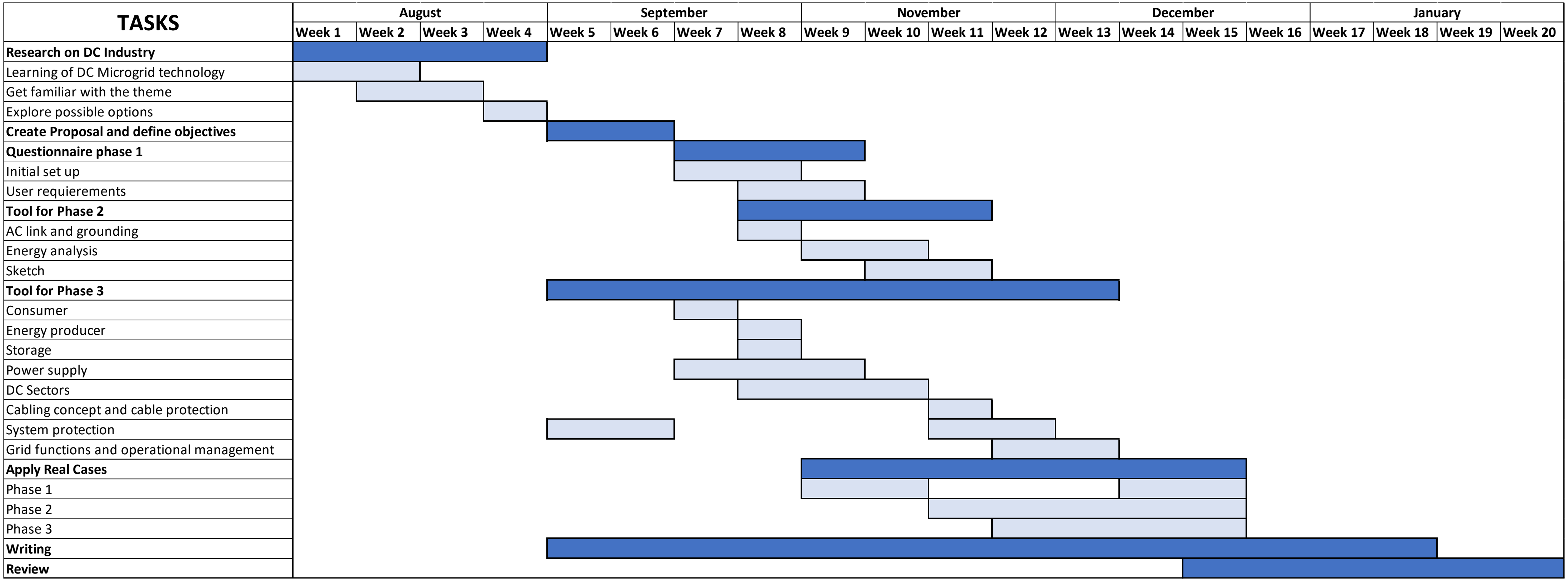


Figure 55: Gantt Diagram

8.2 Economical analysis

In this section the economic analysis of the designing and modelling of a DC Microgrid will be described. An accurate analysis of it can pose challenging because of the nature of the project. DC microgrids is a very innovative topic with not many projects already realized. Also, it is constantly evolving, being subject to changes in the industry and therefore, altering the parameters on which is based on.

In order to make the analysis more visual and understandable, it has been decided that a comparison between AC and DC systems should be made, taking into account the capital expenditure (CAPEX) and operational expenditure (OPEX) of both of them. Also, it will be compared with the predictions for the DC system in 10 years, which will have gone through a large evolution, as it is now in the initial stages.

CAPEX

Costs	AC system	DC system NOW	DC SYSTEM 2030
Equipment costs	High costs	High costs	Equal-lower costs
Engineering and design	Normal costs	Higher costs	Slightly higher costs
Installation	Higher costs	Equal costs	Equal-lower costs

Figure 56: Table for comparison of CAPEX

Regarding the CAPEX comparison, although right now the costs for a DC system installation will be higher than the AC system, the future seems different. Obviously, new technology will initially be more expensive to install than the usual one that has been used for a large period of time. The change will be obtained with continuous investigation and with the increment of projects regarding DC Microgrids. By 2030, the possible costs could be reduced, making the DC System more affordable than the AC system as there are a lot of components and machines that would not be necessary and the installation process would be more automated, making the costs to decrease.

OPEX

Costs	AC system	DC system NOW	DC SYSTEM 2030
Ongoing maintenance	High costs	Lower costs	Lower costs
Monitoring and control systems	Normal costs	Lower costs	Lower costs
Efficiency	Higher costs	Normal costs	Equal-lower costs

Figure 57: Table for comparison of OPEX

Regarding the OPEX costs, the situation is the opposite. The costs associated with maintaining the system and the monitoring and controlling of it are already lower than for the AC system, making the DC system a more viable option in the long run. Because the efficiency of the system will improve, the costs related to it will also decrease. Also, as time goes by and more research is done on the subject, the costs regarding this point will also be lower.

9. CONCLUSIONS

Looking at the project's scope and objectives, two main topics are tackled, first the possibilities that the DC Microgrid technology can bring to an industrial site and the lack of information about this topic, and second, finding the best method to implement this technology in the most efficient way.

It can be stated with the obtained results and the description of the methodology that the objectives of this Master's Thesis have been fulfilled. Although it is complicated to create a general guide that can be followed in order to design an industrial site, this project covers the most important aspects of it, creating a very useful tool that can be used in different cases.

Taking into account that real cases have been used as models for the completion of this project, the value that it gives increases manifold as real companies can use information of this tool that will definitely be useful to them as it has been proven before in real life.

Another important aspect of this project is the division of the phases and how they are connected between them. The order and correct order of how the different phases and subphases is crucial for the correct execution of the project. The creation of such a structured mainframe becomes the key of success for the tool being efficient and manageable for all possible cases. This aspect can be seen especially in Phase 3, which includes the largest number of subphases and follows and iterative method, making the organization and arrangement gain importance.

One of the most important and difficult hustles of the project is the content of each of the phases and subphases. This tool is meant to be followed and used as a main guide, but the designing of a project of this scale includes many aspects that are not mentioned on this guide. Obtaining the right balance between content and simplicity is a key point for the success of this tool.

Through the document, different comparisons have been made between the AC system and the DC system. This is inevitable as they are the only possible alternatives, and the AC system has been the preferred option for a long time. This project also shows how DC systems are a viable option and, in some respects, they resemble an AC system sharing a lot of different concepts and procedures.

From this comparison, looking at the results of the project, it is clearly stated the possible benefits of the DC Microgrid in the energy transition that the world faces nowadays in comparison with the conventional AC system. Also, regarding the economic aspects, although there is still a lot of room of improvement, it already shows some differences with the AC system such as the reduction of needed material or important equipment. This will result in cost reductions.

To summarize, the successful completion of this project has produced a tool that may be used on the innovative projects involving the implementation of the DC Microgrid in an industrial site giving insight and directions on the steps that need to be taken in order to design and model the electrical system for this kind of systems. The insights into DC industry given in this project will also lay a basis to future improvements or changes that need to be made to reach the goal of making DC Microgrids another option for the electrical system of an industrial site.

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11. APPENDIX

11.1 Questionnaire Phase 1

LOCAL SET UP

Existing Infrastructure

Which type of grounding should be used?

Are there specific existing AC or DC connection points?

Are there any existing power rails/cables to be used?

Is there an existing decentralized power generation to be integrated? (e. g. PV, CHP)

If PV is present: Is there an energy profile?

Is there already energy storage to be used (e. g. battery)

Location

What is the location of the power supply inside the factory?

What distance exists from the power supply to the load?

What distance exists from the power supply to the transformer?

What distance exists from the power supply to the transformer?

What distance exists from the transformer to the PV, Batteries, …?

Cooling

What cooling options for components are required/available/allowed?

Sound

Are there noise limit values?

PV-Regulations

If necessary, which PV regulations in DE, EU or international should be considered?

AC-Grid-Country

How high is AC voltage, AC frequency? (400V/50Hz, 480V/60Hz, ...)

How good is the current grid stability/quality?

Are there specific standards/guidelines to be observed?

AC-Grid-EVU (electricity and energy suppliers)

Are there any limitations to the continuous performance?

Is there a maximum permissible peak performance?

If applicable, what is the allowable return power?

Are there particularly high or low energy prices to be considered?

Is there a data connection to the EVU? (e. g. smart grid)

AC-Grid-Factory

Is there a medium or low voltage distribution in the factory?

Are there any restrictions on the permissible medium/low voltage power for the installation?

Is there a separate transformer for the DC grid?

USER REQUIEREMENTS

Load

How high is the sum power requirement and what should be used in the DC area (e. g. light, air conditioning, . . . list of devices)?

Is a simultaneity factor considered?

Producer

Is a high-performance local energy supply planned for self-sufficiency, CO2 reduction or island grid operation? (e. g. PV, CHP, battery)

If yes: should the network be operated autonomously (black start)?

Back feeding / Usage of the grid

Should regenerative energy be fed back into the AC grid?

Should the system be operating grid friendly?

Storage / Grid quality

Should a balancing of power peaks or a reduction of the connection power be implemented?

Are there grid errors or outages that need to be bridged?

Producer / Supplier

Are there components or sub-systems that need to be designed redundantly or otherwise protected against failures?

Connection / Supplier

Should power reserves be planned in order to be able to expand the plant successively in the future?

Priority of application

Are there any production processes that need to be prioritized?

Selectivity

Can one part of the system fail if a short circuit occurs in another part of the system?

Wanted control system

Which control of the system is desired? (Decentralized control, decentralized control with communication, centralized control)

11.2 Questionnaire Phase 3

Energy consumer

How many loads does the system have?

What is the nominal power of each of them?

What is the load factor of each of them?

Is there any energy profile for each of them?

Are there any special specifications of the machine or the drives individually that should be known?

Energy producer

Is it possible to integrate new decentralized energy? If yes, which should be the target value?

Will there be power fed to the AC grid?

Energy storage

What time frame should be aimed for?

Active Infeed Converter

Is there any plan of expansion in the future?

Is redundancy needed?

DC Sectors

What dependance exists between the loads?

Is there a cluster of loads?

Cables and cable protection

Is there any floor plan?

What will be the ambient temperature of the industrial site?

Protection and selectivity

Are short circuits or overload faults occurring?

Is selectivity a must? If yes, is it needed for all the system?

Grid functions and operational management

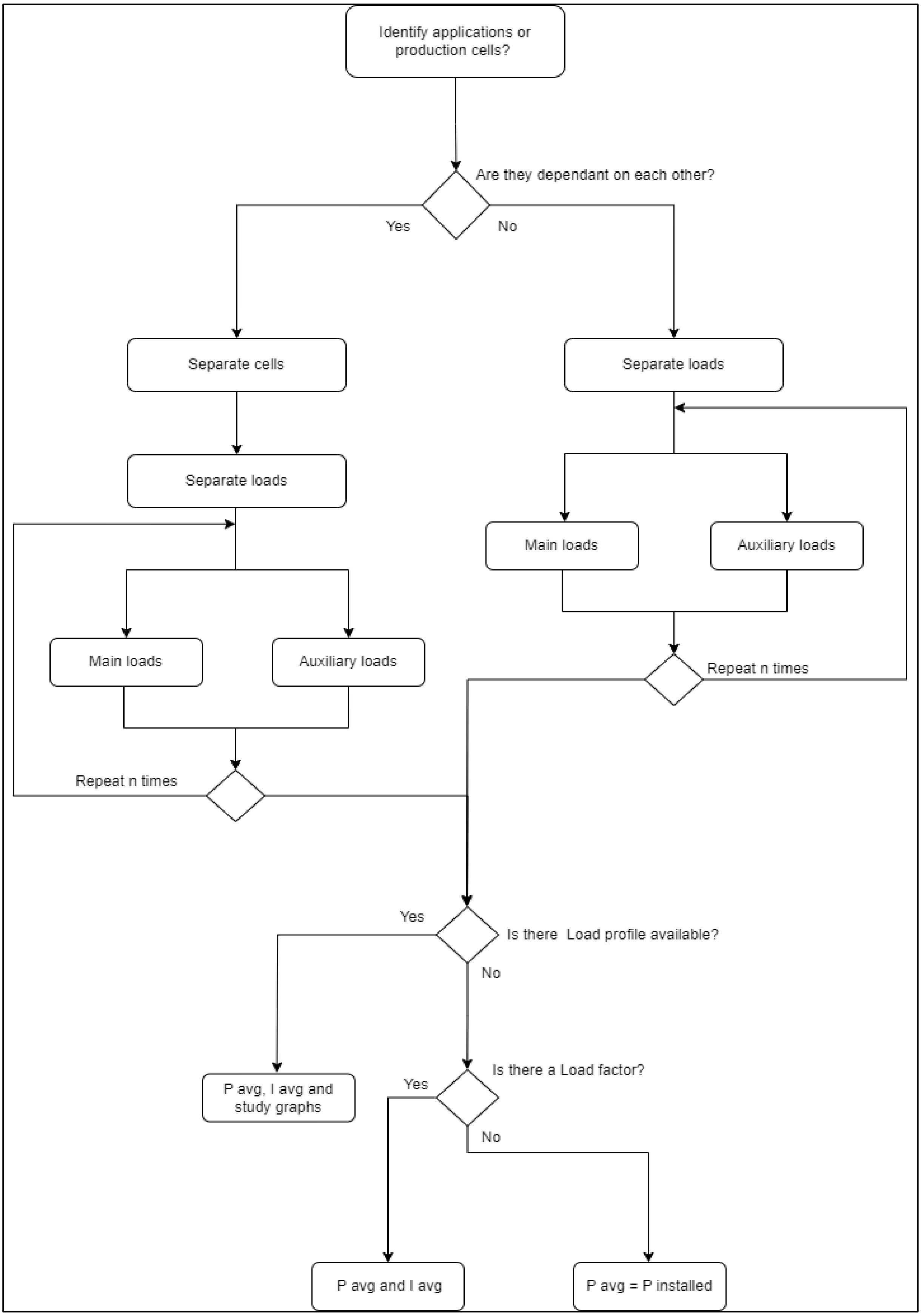
Is energy management needed?

Is power management needed?

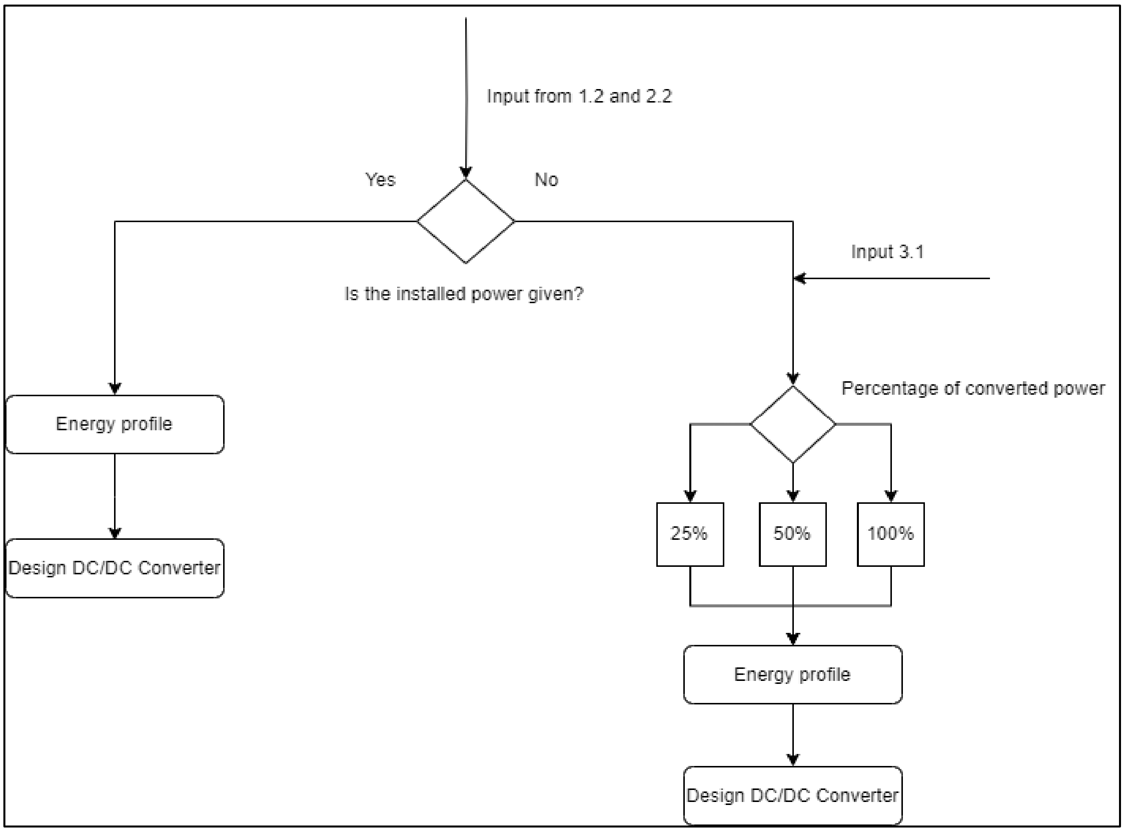
Should we aim for AC-grid support? If yes, what kind of support?

11.3 Flowcharts Phase 3

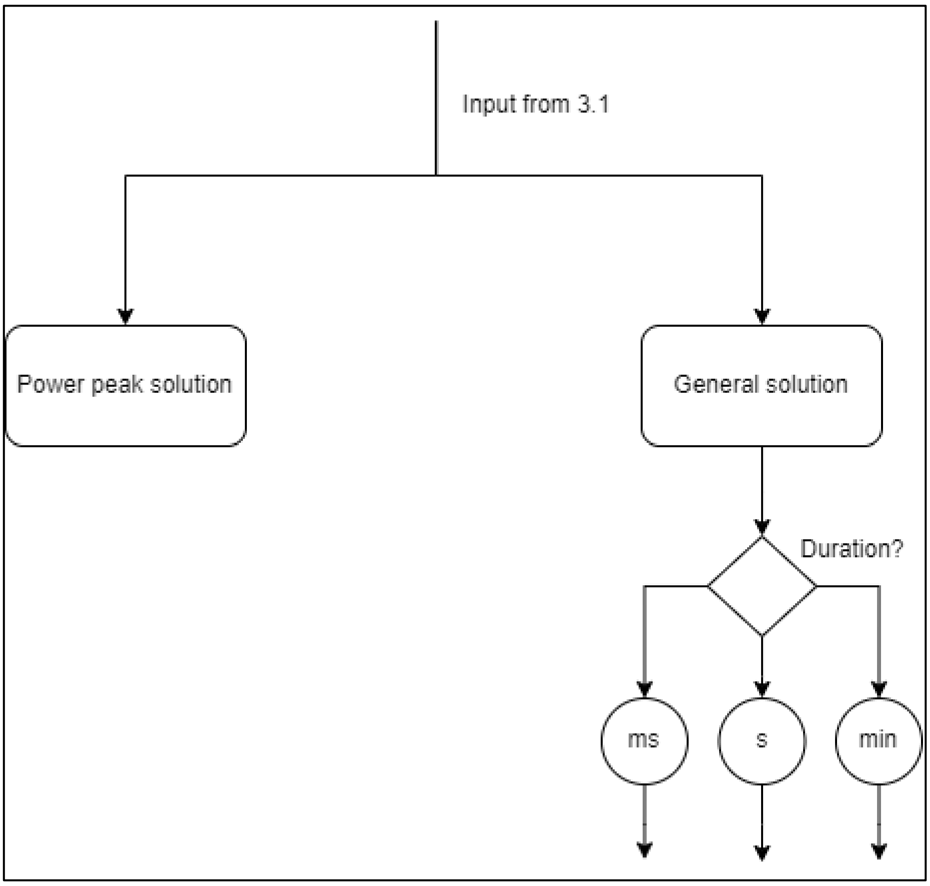
3.1 CONSUMER



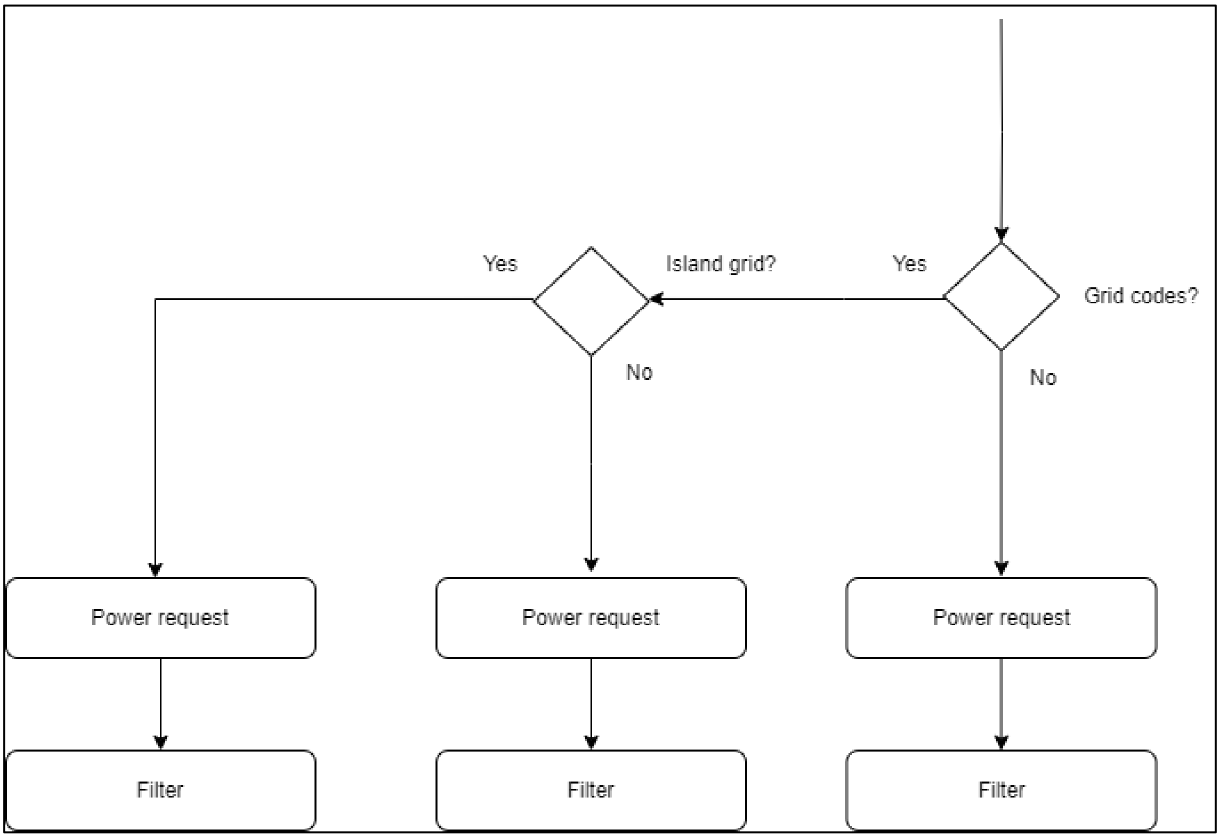
3.2 ENERGY PRODUCER



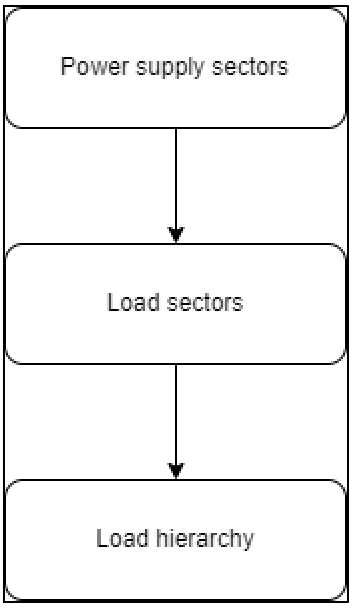
3.3 STORAGE



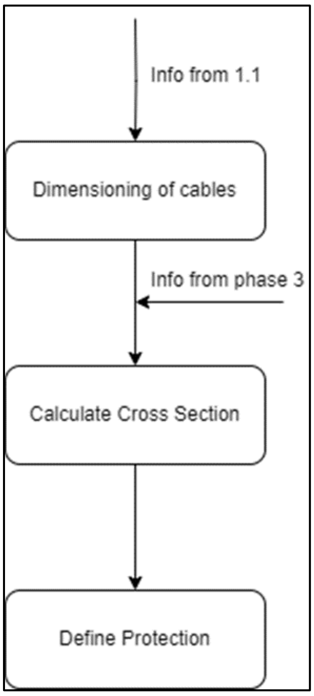
3.4 ACTIVE INFEED CONVERTER



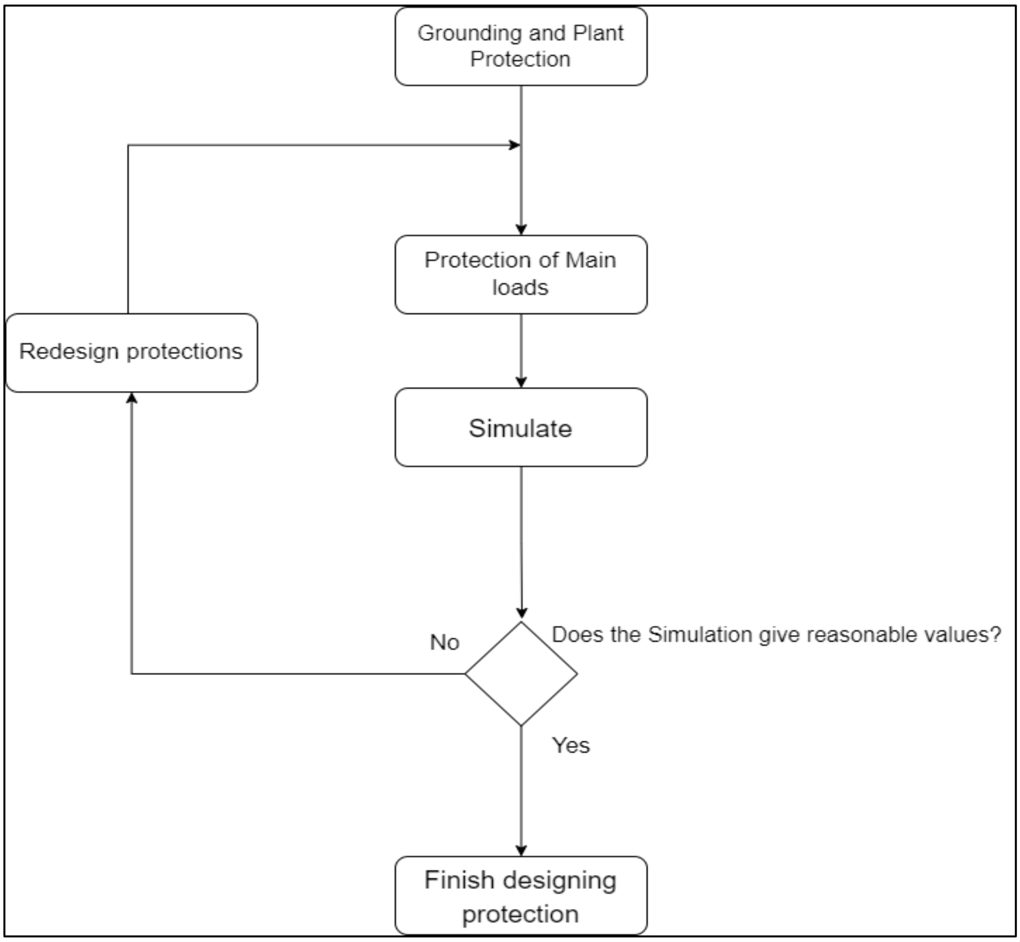
3.5 DC SECTORS



3.6 CABLE AND CABLE PROTECTION



3.7 SYSTEM PROTECTION AND SELECTIVITY



3.8 GRID FUNCTIONS AND OPERATIONAL MANAGEMENT