Techno-Economic Feasibility of an Electric Transition for Fuel/Gas Stations

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Abstract

This report proposes the technology of a DC-Microgrid as a solution for the energy transition of a gas station. Some of the major concerns addressed by this alternative are the environmental impact caused by the insertion of Electric Vehicles (EVs), the resulting shortage of public charging infrastructure for the users, and the technical limitations of the current electrical infrastructure.

Extensive research on the building blocks of a Microgrid was summarized. Then, four Microgrid designs were dissected and reflected upon. Finally, a step-by-step design process was described for a DC-Microgrid capable of providing fast DC-charging and single-phase AC-charging with a maximum output power of 50 kW and 7.4 kW respectively. This power is provided by a mixture of Distributed Energy Resources (DER). The mean power demand is covered by the grid and a PV-module arrangement while the Energy Storage System (ESS) deals with the peak power demand. MATLAB was used to calculate the most optimal values for some of the proposed specifications such as the size of the ESS, energy demand, and power demand.

The proposed solution was found to be a great alternative for the future of energy distribution. It is preferred for the insertion of renewable energy resources due to the fewer transformation steps required. And its superior controllability of power flow and power level allows for increased output powers while maintaining high safety and relatively low costs.

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Chapter 1

INTRODUCTION

The concept of Energy Transition has become one of the biggest concerns in our current society. Broadly speaking, Energy Transition is the radical shift from a fossil-fuel-based to a zero-carbon-based energy sector by 2050 [5]. Multiple reasons are pushing this transformation, some of which are the increasing energy demand, the depletion of fossil fuels, and environmental concerns. Given the huge scale and complexity of this challenge, multiple angles and sectors have to be considered. The transportation sector accounts for 16% of global greenhouse gas (GHG) emissions [6]. This is because most of such transportation is powered using fossil fuels. Just in The United States: gasoline, distillates, jet fuel, and natural gas represent around 92% of the energy sources for transportation [7].

Electric vehicles (EVs) are positioning themselves as an alternative way of transportation that relies on electricity as an energy source instead of fossil fuels. In addition, with the technological advancements in this industry, EVs have increased their performance to be compatible with urban mobility needs. This has fueled their proliferation worldwide. It is estimated that in 2019 there were 4.79 million electric vehicles in circulation and are sold by numerous car manufacturers such as Audi, BMW, Chevrolet, Ford, Porsche, Tesla just to name a few [6] [8].

Nevertheless, the advance of Electric Vehicles alone is not sufficient. Various concerns have arisen with the idea of the mass insertion of EVs to the roads. From the consumer point of view, the rapid adoption has resulted in a significant increase in charging stations in private settings. However, the increase of public chargers is lagging significantly [9]. Such slow development of infrastructure acts as a deterrent for EVs acquisition since people are limited to the places where they can charge their vehicles and therefore limited to the places they can go with it. This is particularly troublesome for cargo vehicles that need to travel long distances without refueling [6].

On the other hand, if an expansion of the charging infrastructure is considered, there are technical challenges that need to be addressed. One of the biggest concerns is the high distress that can be caused in the grid just because it was not designed for this purpose. The immense investments and workforce required for the adaptation and even replacement of the current system are not acceptable. And even if they were, the current resources powering the grid are still predominantly fossil fuels which go against the principles of Energy Transition [7]. Thus, the main questions to be addressed in this report are: how can the electrification of a gas station be a feasible solution to diminish the negative consequences of the insertion of Electric Vehicles? And what is the most suitable alternative to achieve such energy transition from a technical point of view?

Taking the above into consideration, the system known as Microgrid presents itself as a viable solution. The main features of this alternative are its flexibility of operation, efficiency, insertion of renewable energy sources, and controllability [10]. It has been widely described in literature such as [11] [1] [12] as well as used in real-life applications, predominantly to power houses of small communities or even islands [13]. Nevertheless, there still exists plenty of literature describing the application of Microgrid to charge Electric Vehicles [14] [7].

With that base, this writing will describe the technologies involved in a Microgrid, evaluate the existing solutions, and prescribe the best combination, if any, that allows for a successful Energy Transition of a fuel station. The report will be structured as follows. First, the different alternatives to power generation will be briefly outlined. Then, a concise description of what is a microgrid as well as its classification will be presented. Next, I will go through the charging modes available for EVs. After this, special attention will be put on two of the main elements of a Microgrid: Power Converters and Energy Storage Systems (ESS). With this information, I will go ahead and present the final design of the Microgrid while explaining the thought process involved. The report will be closed by a brief conclusion of the findings.

Chapter 2

DISTRIBUTED ENERGY RESOURCES

Increased environmental concern, energy demand, and energy costs fluctuation have resulted in the rapid adoption of the DER technologies. These are described as decentralized, small-scale (3kW - 50 MW) power generation systems. This section describes some of the major resources being used for the purpose of Energy Transition and reflects on their utility for this research project [15].

2.1 Solar Energy

The generation of power using the sun is achieved using what is known as Photovoltaic (PV) Modules or solar panels. PV modules convert the sun irradiance into electrical power. Given that the irradiance of the sun does not vary in a short period of time the output power of a PV module resembles a DC signal. Some of the main advantages of this system are its renewable nature, the generation of power without movable parts, and no emissions. On the other hand, some of the disadvantages of this source are its intermittency and the low efficiency they have when converting solar power into electrical power: $\sim 20\%$ [15].

2.2 Wind Energy

The tools used to collect wind power are known as Wind Turbines. Unlike PV modules, wind turbines do not produce a DC output since their power generation relies on the velocity of the wind which is variable by nature. One of the main advantages of this technology is its maturity and renewable nature. The disadvantages are their intermittency, the output power is highly dependant on the location's wind speed and high initial costs [15] [13].

2.3 Biomass Energy

This type of power generation is achieved by the use of living or once-living organisms. As shown in [13], tools such as wood stoves can be used. In this example, wood is being burned at high temperatures in order to ensure maximum efficiency. The generated heat can be used in various forms e.g heat is used to boil water and power turbines that generate electricity, or directly use the heated water for applications such as underfloor heating. The most obvious advantage is the fact that it is readily available and can be used to generate electricity whenever it is needed. The disadvantage is that the rate of use versus generation is not balanced and ends up having an environmental impact.

2.4 Others

There are others Distributed Energy Resources available such as microturbines, combustion turbines, stirling engines, fuel cells, and hybrid systems just to name a few [15]. Nonetheless, such systems are early on the maturity stage of the technology, or the principle on how they function goes against the goal of this research project. Thus, they will not be considered for this writing.

2.5 Energy Storage

This is not a power generation method as such since it requires another source of energy in order to store it in the first place. However, once charged, it is capable of providing power for a limited period of time for which it is also considered as a DER technology. The advantage of this system is that it can provide a constant output power on command which is useful when unforeseen circumstances happen or to compensate intermittent energy resources. The disadvantages are the limited capacity they have, high costs, and the non-renewable materials used to build them [15]. There are various considerations that need to be taken when choosing an Energy Storage System. These will be outlined later in this report.

Chapter 3

MICROGRIDS

A Microgrid can be described as a controllable low-power distribution network that comprises Distributed Energy Resources, loads, Energy Storage Systems (ESS), and control blocks. In general, a Microgrid operates in the range of kilo-Watts up until a few Mega-Watts. The main objectives of such systems are to improve power supply reliability, energy efficiency as well as to speed up energy transition because of the insertion of renewable DERs [11][1]. This section will describe the different classifications for microgrids found in the literature and highlight the benefits as well as the drawbacks they pose towards the goal of this report.

3.1 AC Microgrids

An AC-Microgrid is described as a distribution network that interconnects its elements using an AC bus. This type of microgrid can further be divided into High-Frequency AC (HFAC) Microgrid and Low-Frequency AC (LFAC) Microgrid. The HFAC microgrid involves frequencies of 400-500 Hz. It allows for a compact design since the size of its filter can be reduced due to the higher frequencies. However, it does result in higher complexity, costs, and operating losses since more AC-AC converters are required to decrease the frequency to a standard value: 50-60 Hz (LFAC frequency). The advantages are that this typology does not require an extra inverter to inject the power to the grid and the maturity of its technology. On the other hand, the control is more difficult. More disadvantages that this typology brings will be introduced in the DC-microgrid description[11] [1]. A typical block diagram for an AC-Microgrid is presented in figure 3.1

3.2 DC Microgrids

A DC-Microgrid is a distribution network that interconnects its elements using a DC bus. According to literature [11] [1], this configuration is preferred over the AC-Microgrid for the following reasons:

- They are significantly more efficient for Distributed Renewable Energy Resources.
- They usually deal with low DC voltage which is considerably safer than AC voltage.
- No skin effect on the conductors. In other words, the full cross-section of the transmission lines is being used.
- Pushes the use of DC loads which are generally more power-efficient.

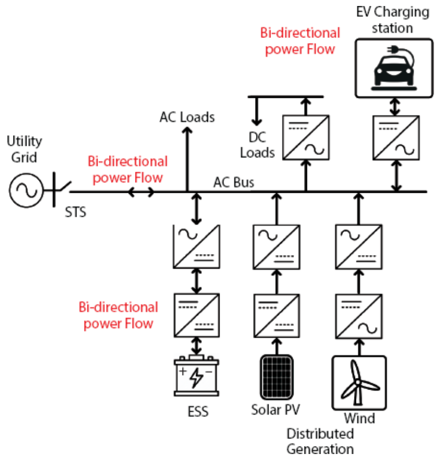

Figure 3.1: Typical Block Diagram of an AC-Microgrid including DER and EV as DC load[1].

- Ease of power flow control by controlling current flow while maintaining the same voltage polarity.
- Synchronization is not required which results in less complexity of the circuit.
- No reactive power loses.

A more thorough comparison of AC and DC technologies is done in [16] where the benefits of a DC microgrid are emphasized. On the other hand, the disadvantages of a DC-Microgrid are the undeveloped technology, lack of regulations and that it requires inverters when AC loads or AC DER are connected. A typical block diagram for an DC-Microgrid is presented in figure 3.2

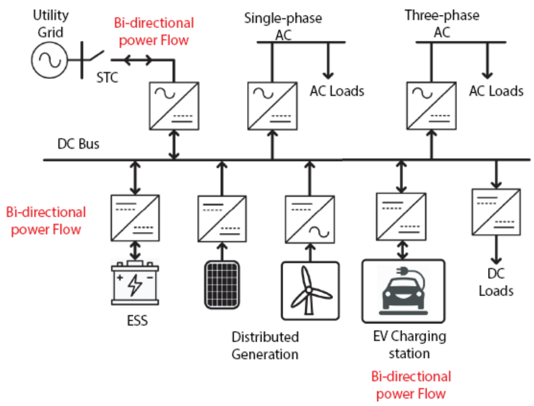

Figure 3.2: Typical Block Diagram of an DC-Microgrid including DER and EV as DC load[1].

3.3 Hybrid Microgrids

In essence, this configuration is the result of joining a DC and an AC-Microgrid via a power converter. This type of distribution network has the advantages and disadvantages of both AC and DC Microgrids. The main idea of a Hybrid Microgrid is to incorporate a wider variety of Distributed Energy Resources without the need for additional power converters as is the case in an AC-Microgrid when using PV modules as a power source for example. Nevertheless, the increased flexibility comes at the cost of the higher overall complexity of the system[11]. According to [16], this configuration of Microgrids might be an intermediate step to shift to DC-Microgrids while their technology and regulations mature. Figure 3.3 shows a typical block diagram of a hybrid Microgrid. It can be clearly seen how a both a DC-Microgrid and an AC-Microgrid are joined by means of a power converter.

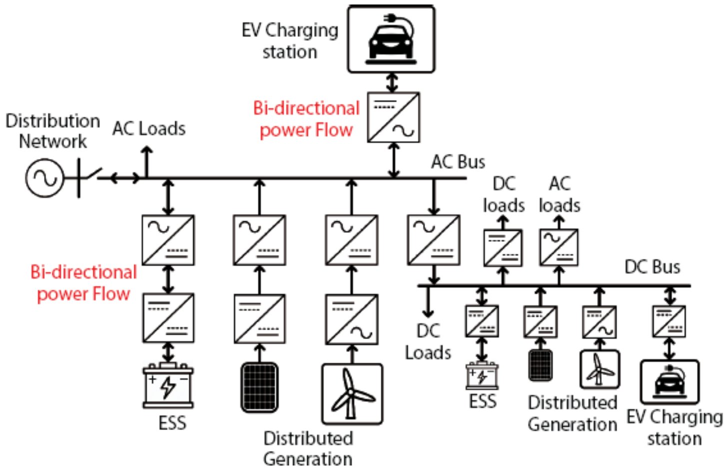

Figure 3.3: Typical Block Diagram of a Hybrid Microgrid including DER and EV as DC load[1].

3.4 Operational States

The classification of the microgrids can be extended to the modality in which they operate.

3.4.1 Islanded Mode

One of the main advantages that a microgrid offers is its ability to fully function on its own. All the power is provided by DER technologies. This is ideal for the electrification of remote places such as islands where is not feasible to bring the infrastructure of the main grid [17] [12].

3.4.2 Grid-Connected Mode

This operational mode refers to the coupling between a microgrid and the grid. This mode requires the synchronization of both power resources. In general, this modality is required when the power for the loads attached to the microgrid is higher than the one provided by the DER. In addition, this operational state also allows the microgrid to provide ancillary services in the case of excess power generation from the DERs [12].

Chapter 4

ELECTRIC VEHICLES CHARGING MODES

Given that the main focus of this project is on the energy transition of a fuel station, the only load of the Microgrid to be designed will be an Electric Vehicle. Thus, it is important to dive into the charging modes available for such load. These modes are regulated by the IEC 61851-1 and will serve as guidelines for the final design of the microgrid. Furthermore, this section will reflect on the advantages and disadvantages of each mode towards the purpose of this research [2].

4.1 Mode 1

This charging mode refers to the direct delivery of AC power to the built-in converter of the Electric Vehicle. The main advantage of this mode is that it can be carried out virtually in any place with a grid connection. The downside is the limited output power that is allowed for this mode: 3.3 kW, single-phase, 16 A [18]. This mode is presented in figure 4.1.

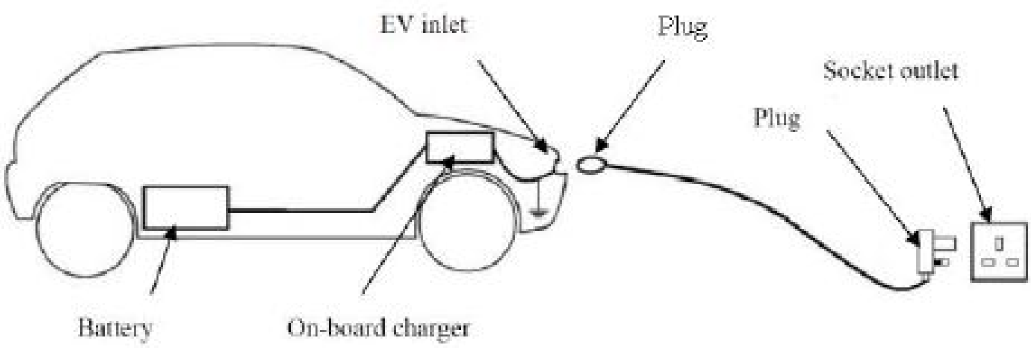

Figure 4.1: Mode 1: single-phase AC-charging[2]

4.2 Mode 2

This mode requires an In-Cable Control Box to manually manage the charging capacity depending on the load. This extra feature also increases the allowed maximum AC output power: 7.4 kW for a 1-phase, 32 A connection, or 22 kW for a 3-phase, 32 A connection. The positive aspect of this mode is its increased power capacity. It is worth remarking that anything above 22 kW can be considered as fast charging. Nonetheless, this mode still required manual input which can lead to misuse due to human error [2]. This mode is presented in figure 4.2.

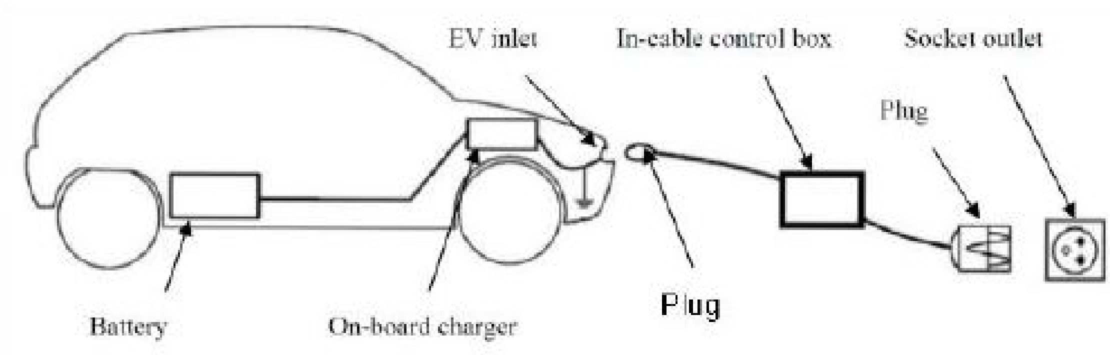

Figure 4.2: Mode 2: single-phase, three-phases AC-charging with in-cable control box[2]

4.3 Mode 3

This modality introduces the direct communication between the EV and the charging station in order to define the charging capacity. In mode 3 the most common output power is 11 kW, 22 kW, and on some occasions even 43 kW. The main advantage is the automation of charge thanks to the Vehicle to Charger (V2C) communication [2]. However, according to a conversation held with Evert Raaijen from Alfen "It cannot be claimed an increase in power as another advantage since a 43 kW output power in AC chargers is rarely found, even 22 kW is in the high end". This mode is presented in figure 4.3.

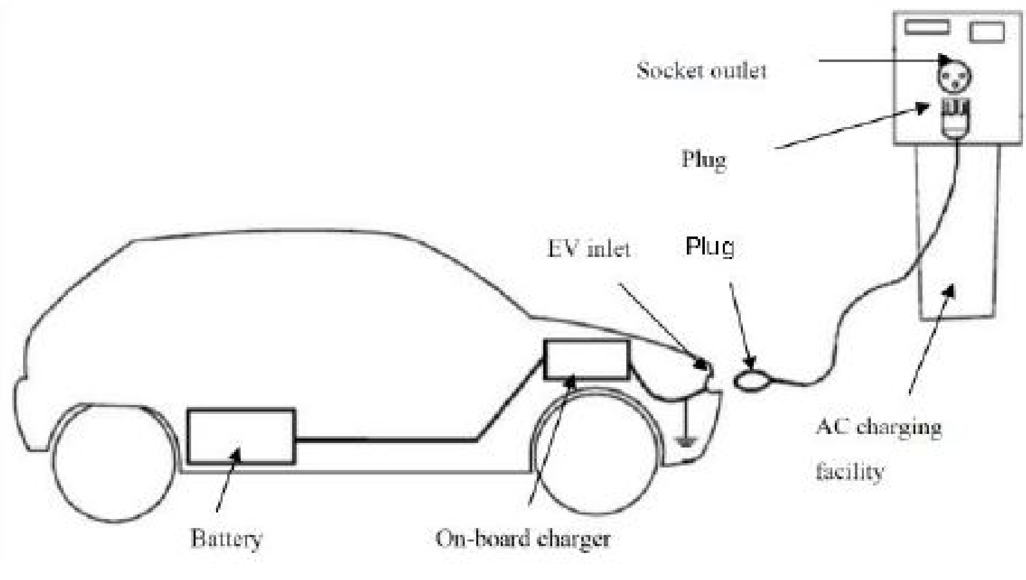

Figure 4.3: Mode 3: single-phase, three-phases AC-charging with direct communication with EV[2]

4.4 Mode 4

The last mode introduces the delivery of DC power. The main advantages of this mode are the V2C communication and the fast charging due to the increased output power: from 50 kW to 175 kW. Chargers with bigger output power are being developed, however, this has to be done in parallel with the development of batteries that can support this stress[2]. A rather obvious, nonetheless important detail, is to recognize the fact that the battery of an EV has to be charged using DC power. In modes 1 to 3, the conversion from AC to DC power is being done in the built-in converter of the EV. Mode 4 requires this conversion to be performed in the charging station itself. This because the converter size is substantially bigger in order to support the higher output power [19].This mode is presented in figure 4.4.

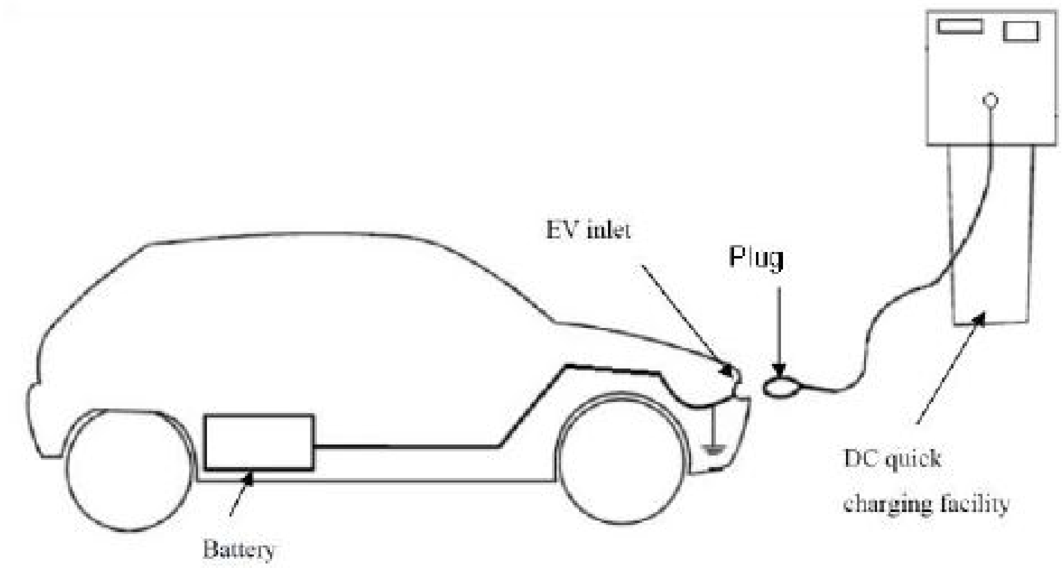

Figure 4.4: Mode 4: DC-charging with direct communication with EV[2]

Chapter 5

POWER CONVERTERS

The previous sections have described power resources (DERs), a way to distribute this power (Microgrid), and how to deliver it to the final load (Charging Modes). This section will describe one of the key elements to interconnect these three aspects into the Microgrid: Power Converters. As the name suggests, these devices are capable of changing the shape, regulate or boost the signals coming from the DERs up until its delivery to the load i.e Electric Vehicle. There are numerous types of power converters depending on various aspects such as the load or the type of microgrid. Thus, a description and analysis of the typologies will be drawn below[20] [16].

5.1 AC-DC Power Converter

These converters are also known as rectifiers. The main idea is to transform an input alternating signal, such as the one coming from the grid to a constant or rectified output. The typology to be used depends on whether the input is a single-phase or a three-phase alternating signal. Similarly, different requirements for the output such as the acceptable Total Harmonic Distortion (THD) define the type of rectifier being used. The most common typologies being used are:

- **Single-phase grid:** Single-phase diode or single-phase thyristor rectifier. This circuit is also commonly known as a full bridge rectifier [20].
- **Three-phases grid:** The 6-pulse rectifier is the most basic typology. This configuration can be used as a building block for a 12-pulse, 18-pulse, or 24-pulse rectifier. If a bidirectional power flow is required the 2-level and 3-level line converters are mentioned in the literature [20] [3] .

5.2 DC-DC Power Converter

This type of converter has a DC signal as input and output. The main goal of a DC-DC converter is to change the level of the output voltage. In general, these converters are composed of power switches such as the MOSFET controlled by pulses with a duty cycle dependent on the required output. In addition, this converter can be used in tandem with an MPPT to obtain the maximum output power out of a DER. With that basis, there are three main categories or architectures [21] [20]:

- **Boost type converter:** this DC-DC converter increases the level of the input voltage.

- **Buck type converter:** this DC-DC converter decreases the level of the input voltage.
- **Buck-Boost converter:**as the name suggests, this converter is a combination of the buck and the boost converter. It is used to both increase and decrease the voltage level.

These converters can further be categorized into isolated and non-isolated converters. Isolated converters use a high-frequency transformer to separate the input from the output. This is preferred for safety reasons. On the other hand, non-isolated converters are preferred due to their lower losses, costs, size, and no core saturation issues [21].

5.3 DC-AC Power Converter

This converter is used to transform a DC input signal into an AC output. For example, a DC-AC converter is required when injecting the power collected from a PV module which is DC to the grid which is AC. In the case of a DC bus, this converter is used to provide power to an AC load.

This converter is usually controlled using the Pulse Width Modulation (PMW) technique. At high power, the switching frequency is limited by several factors such as switching stresses on the power devices, switching losses, and electromagnetic interference caused by the drastic $\frac{dI}{dt}$ and $\frac{dV}{dt}$. In order to address such limitations, let us describe a categorization for DC-AC converters:

Hard-switching DC-AC converters: AC power devices or loads are directly connected to a stiff voltage source inverter (VSI) or to a stiff current source inverter (CSI). This direct connection causes switching losses and EMI problems when there are sudden changes in voltages and currents [22]. The inverter can be single-phase or three-phases, although the latter is usually not required. Furthermore, the inverter can be either half-bridge or full-bridge. The full-bridge configuration is more complex but the passive elements required before and after the inverter can be smaller [20].

Soft-switching DC-AC converters: In essence, it is a hard-switching DC-AC converter with an additional high-frequency resonant network. This network can be composed of only passive elements such as inductors and capacitors, but in some configurations, diodes and switches are also used. The main purpose of the network is to shape the switching waveform which reduces losses, switch stress, and EMI [22].

Chapter 6

ENERGY STORAGE SYSTEM

Most of the DER are quite rigid in their specifications. They are either limited by the physical space available, as is the case of solar panels, or limited in terms of resources as is the case of biomass. The ESS is crucial to compensate for such limitations and ensure a more reliable system overall. This section will elaborate on the considerations that should be taken when designing an Energy Storage System [23].

6.1 Load demand

This parameter indicates the required energy demand according to a specific time period. The span of such a period can vary depending on the system being developed. Such a figure is particularly important in order to understand whether most of the consumption is being while the sun is shining or not. Furthermore, a load demand profile also shows the peak values of demand which might be valuable information to account for the protection of the system being developed.

6.2 Solar Potential of the Area

This indicator will consider three values. First, we start off with the solar irradiance or the power received from the Sun per unit area, the SI unit is Watt per meter squared ($\frac{W}{m^2}$). This value does not represent much by itself for which it is typically integrated over a period of time. For our purpose, the irradiance will be integrated into Watt-hour per squared meter [$\frac{Wh}{m^2}$], this is known as solar irradiation or insolation. Lastly, we will consider the Specific Photovoltaic Power. This represents how much energy (kWh) is produced from every kWp of solar panels capacity. In other words, the yield of your PV modules arrangement, a typical value is between 1000-2000 $\frac{kWh}{kWp}$ in a year. This figure can be used in conjunction with the load demand to determine whether there is enough energy supply solely from a renewable source [24][25].

6.3 Desired hours of Autonomy

This parameter describes how many hours of autonomy should be provided by the Energy Storage System. The resulting number is defined by several factors completely dependant on the use case scenario for which an exact recipe cannot be described. However, it is no surprise that one of the biggest factors is the load demand.

6.4 Allowed Depth of Discharge

In short, this value shows what percentage of the storage device i.e the battery, can be consumed. For example, if a battery has a capacity of 500 Ah with a 20% DoD, the available capacity will be $500 \cdot 0.2 = 100Ah$.

6.5 Efficiency of ESS

This value specifies how much of the energy can be extracted out of the inputted energy into the battery. In other words, this can be described as energy transformation efficiency.

6.6 C-Rate

This value tells you what is the speed of charge or discharge of the battery. A 1C discharge rate means that the full capacity of the battery will be used within 1 hour, a 2C discharge rate means that the full capacity of the battery will be depleted within half an hour or 30 minutes while a 0.5C means that it will take 2 hours for the battery to fully discharge.

Chapter 7

USE CASE SCENARIO: DESIGNING THE MICROGRID

The previous sections have described the main elements for the design of a Microgrid. This section will consider all that information and select the best options from a technical point of view. The final design has as objective to contribute to the technical feasibility of an electric transition of a fuel station. This will be achieved by following the design process described in [26].

7.1 System Top Level

This section has as objective to describe the system requirements and key drivers of the microgrid. This has to be done keeping in mind a balance between the customer's wishes and the supplier's capabilities. In this context, I will be acting as the supplier and will define what are the allowed requirements from a technical point of view.

7.1.1 Functional Block Diagram

The first tool that will be used to define the system requirements is a Functional Block Diagram (FBD). The FBD will display the main functions that the Microgrid should be able to do either sequentially or in parallel. This will help to determine the hierarchy of the functions involved and the circuits or devices in charge of it will be prioritized in the design. The platform Miro was used to sketching the diagram shown in figure7.1.

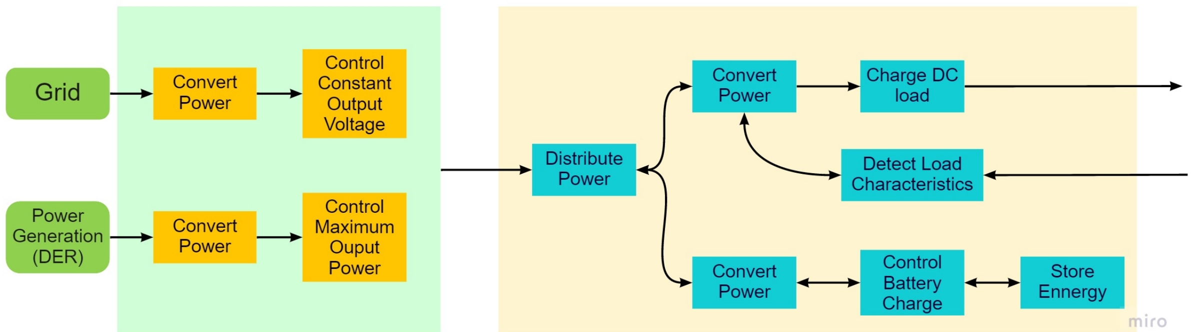

Figure 7.1: Functional block diagram showing the functions of a Microgrid which includes DER as power resource. The system is used collect, store and distribute energy.

7.1.2 System Requirements

The system requirements have as objective to outline the generalized stakeholder's main interest. It should not be confused with the system specifications which describe the technical features of the system, these will be presented later in this writing. Several general requirements for the Microgrid are enumerated below:

- It should efficiently incorporate renewable DER.
- It should be able to satisfy the average EV charging demand of one charging station in The Netherlands.
- If it must collaborate with the grid to satisfy the demand: It should not motivate radical changes to the current grid infrastructure or cause detrimental stress to it.
- Its design should be easily replicable. That is, it uses already available or accessible technology.
- It should follow established regulations.
- It should be robust to climate and energy demand variations.

7.2 Feasibility: Four Examples of a DC-Microgrid design

Now that the basic requirements have been established, it is possible to carry out desk research to evaluate the feasibility and added value of our design. In the following paragraphs, I will evaluate some Microgrid designs that resemble the aim of this research project. The main characteristics will be highlighted and possible points of improvement, if any, will be described.

Given the numerous advantages that a DC-Microgrid presents over an AC-Microgrid [11] [1]. And studies concluding that with the increasing number of DC Distributed Energy Resources, DC-Microgrids are soon to position themselves as the future energy systems [27]. This writing will narrow its focus to DC-Microgrids as the suggested solution.

7.2.1 Example 1: DC-microgrid for the smart integration of renewable sources with urban electric mobility

- Firstly, this paper covers three of the main aspects of this research project: 1) Integration of renewable DER 2) it addressed the problem of urban mobility, and 3) it aims to reduce the electric power supplied by the grid as much as possible.
- It uses a DC-Microgrid with a voltage of 800 VDC.
- The Energy Storage System is designed to provide ancillary services: peak shaving, load balancing, and Vehicle to Grid power transfer (V2G).
- All simulation results presented are based on a laboratory prototype.
- The maximum delivered voltage (to charge the Electric Vehicles) is 288 V.

This design presents a solid use case scenario with detailed modeling of the components of the microgrid. Nevertheless, the chosen voltage is thought to be too high with no explicit justification. This might be a limitation for easy replicability, especially considering the power converters' specifications [7].

7.2.2 Example 2: Design and Modeling of a Standalone DC-Microgrid for Off-Grid Schools in Rural Areas of Developing Countries

- It describes the typologies of the microgrids and presents similar advantages of a DC microgrid over an AC microgrid as the ones presented in this paper.
- It uses a DC-Microgrid based on the loads that will be attached to the microgrid i.e. DC loads.
- The approach to calculating the energy demand is by investigating the required power per load and for how much time it is required. It outputs nice daily loads profiles: Power vs Time of the day
- It considers 3 days of full autonomy using the ESS and a DoD of 80%. No justification for such a period is described.
- The main objective of the ESS will be to regulate power fluctuations. This because according to his calculations the energy generation surpasses the demand.

The strong points of this design are the estimation of energy demand and the justification for the chosen type of Microgrid. However, the decisions behind the design of the ESS were not well described and sometimes seemed arbitrary. Furthermore, the final purpose of the microgrid is to serve low power loads such as light bulbs, computers, fans, etc. This makes the assumption of more energy being produced than consumed, non-applicable for our purpose [28].

7.2.3 Example 3: Design and Analysis of a DC Microgrid with centralized Battery Energy Storage System

- It includes PV modules and wind turbines as DER.
- It uses a DC-microgrid with a bus voltage of 200 V and load capacity of 6 kW.
- It emphasizes the control methods for the power converters. On the one hand, you have the voltage control method which ensures a constant output voltage while the current control method ensures a maximum output power.
- It simulates the variation of the PV energy collected in time with a linear relation.
- The ESS used to stabilize the DC-bus voltage for which a bidirectional power converter is required. This because the microgrid in this paper does not have the grid as one of its power resources.

This design presents clear models of the elements in the microgrid: wind turbine, PV module, power converters. The main downside point is the lack of a connection to the grid which makes this design highly dependent on the power generation of the wind turbine and the ESS. Lastly, the considered load capacity is significantly lower than what is expected of our design [29].

7.2.4 Example 4: Optimum design of an EV/PHEV charging station with DC bus and storage system

- It introduces the concept of fast charging as one of the main characteristics to have if the system will replace a gas station. It emphasizes the fact that AC charging is not capable of fulfilling this requirement for which it focuses on DC charging only.
- It sets up a worst-case scenario where the maximum output power is 240 kW.
- A series of assumptions were made. Some of them are the State of Charge (SoC) of the EV, battery capacity range, charge rate, and the microgrid's efficiency of power transformation. All these parameters were described with a mean and a standard deviation for a robust estimation of the energy demand.
- It implements PV modules as renewable DER.
- The power produced by the solar panels plus the power from the grid should be able to provide for the mean energy demand. The ESS is used to do peak shaving only.

This paper considers most of the system requirements of this research project. A robust and logical estimation for the mean energy demand was presented. In addition, nice design choices for the sizing of the ESS are described. The main issue encountered with this design was first, the currency of its information which dates from over 10 years ago. Secondly, the worst-case scenario considered is too extreme with no proper justification [3].

7.3 Concretization

The next step in the design process is to go from system level to subsystem level. The main objective of this section is to first, specify the building blocks or subsystems of the Microgrid. Second, describe the role and specifications of each subsystem. And third, provide proper justification for the design choices presented.

7.3.1 System Configuration

At this point, it has been established that the complete system is a Microgrid. The subsystems that will compose it have been defined based on the presented theory in sections I-V and in the use case scenarios studied in section VI. Figure 7.2 shows the configuration of a DC microgrid that includes DER, an ESS and the possibility of a DC-load as well as an AC-load. There are two standard voltages used in the DC-bus: 380 V and 400 V with a 10% deviation [30]. The voltage bus of 400 V has been chosen over the 380 V to ensure a higher voltage than the car battery and make the charging possible.

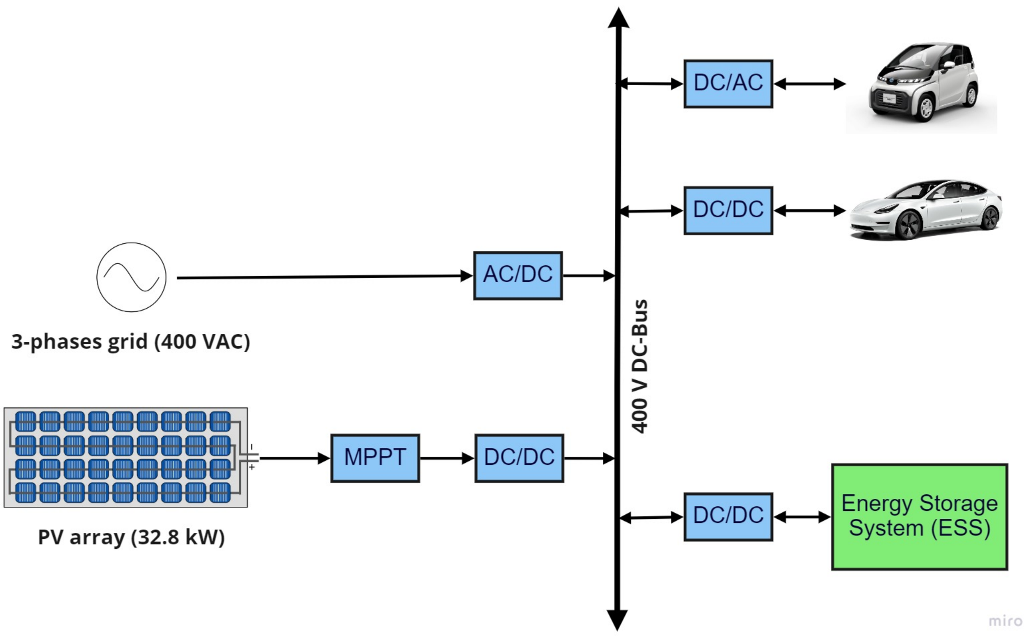

Figure 7.2: System configuration of the proposed DC-Microgrid

7.4 Implementation

This section will detail the design of each of the building blocks composing the DC-Microgrid.

7.4.1 Loads

The first parameter to be defined is what kind of loads will be attached to our Microgrid. As previously stated, the main target load of this design is an Electric Vehicle. This of course presents a challenge for the design given that there are numerous EV models in circulation. The main concern with the variety of models is the changing battery capacity which results in a variable load or energy demand.

For this writing, two considerations will be taken into account. First, the 10 most popular, commercially available Electric Vehicles will be considered as the total number of EVs in the Netherlands. In reality, these represent about 80% of all Battery Electric Vehicles registered in The Netherlands [14]. This is considered to be an acceptable approximation for the purpose of this research project.

Second, the probability of a certain model coming to the charging station i.e the Microgrid will correspond to the percentage of this model on the assumed new total. Table 7.1 shows the models of the EVs being considered in descending order, how many units are on the road, their corresponding probability, and their battery capacity. The latter value will be used in the following section.

7.4.2 Load Energy Demand

This is probably one of the most important parameters to be determined. The sizing of all other subsystems will depend on the power and energy demand. Unfortunately, it is not possible to determine an exact value.

Table 7.1: Top 10 BEV in The Netherlands, the number of units in circulation, battery capacity of each model and the probability of the model coming to the charging station.

N.-	Model	Number of Units in Circulation	Battery Capacity[kW]	Probability of Appearance
1	Tesla Model 3	32 597	47.5	0.323
2	Tesla Model S	12 849	95	0.127
3	Nissan LEAF	9 678	36	0.096
4	Volkswagen e-Golf	8 988	32	0.089
5	Hyundai Kona	7 695	64	0.076
6	BMW i3	6 735	37.9	0.067
7	Renault Zoe 3	6 654	52	0.066
8	Kia Niro	6 130	64	0.061
9	Tesla Model X	5 203	95	0.052
10	Jaguar I-Pace	4 338	84.7	0.043

The next best approach is to use basic probability theory to calculate the mean power and energy demand. The mean is a measure of central tendency and is calculated by the sum of every possible value multiplied by its corresponding probability.

This report considers the load demand to be dependent on two parameters: the battery capacity and the State of Charge (SoC) of the battery as described in equation 7.1.

$$E_{demand} = B\_Capacity - B\_Capacity \cdot SoC \tag{7.1}$$

To that end, the charging behavior of Electric Vehicles has to be considered. According to [31], the probability of people charging at an specific SoC is as presented in table 7.2. Lastly, an extra factor needs to be considered. That is, a specific SoC can correspond to any battery capacity and vice versa. MATLAB will be used to calculate the mean load energy demand and account for this as follows, the complete code can be found in Appendix A:

- First, a sequence of 1000 battery capacities will be generated based on their probability as specified in table 7.1.
- A new sequence of 1000 SoC values will be generated according to the probability shown in table 7.2.
- The first value of the battery capacity sequence will be matched with the first value of the SoC sequence and will be used as inputs for equation 7.1. This will be repeated for all 1000 values. The result is a new sequence with 1000 values for the energy demand.
- The mean of the energy demand sequence will be calculated. This is taken as the mean energy demand in The Netherlands.

According to the simulations carried out the mean energy demand in The Netherlands is 30 kWh. It is worth remarking that this means energy demand corresponds to a single

Table 7.2: Probability of a SoC

State of Charge%	Probability
10	0.01
15	0.09
20	0.01
25	0.04
30	0.14
35	0.04
40	0.1
45	0.09
50	0.1
55	0.09
60	0.1
65	0.09
70	0.03
75	0.04
80	0.01
85	0.01

EV being charged in the Microgrid. This research project was done in parallel to another Bachelor's student whose focus is on the economical aspect. According to his findings, on average each charging station receives a total of 5 EVs per day. With this in mind, the total mean energy demand is taken to be 150 kWh per day.

7.4.3 Distributed Energy Resources

Two energy resources were chosen for this design:

- The grid
- Solar panels

The specifications for each will be described in the following paragraphs.

Grid

In the Netherlands, the local distribution network consists of 3 phases. For most homes, only two of them are used for which the output voltage from a socket is typically 230 VAC. It is possible for businesses to use all three phases upon request which results in an output voltage of 400 VAC. According to the Dutch Net Code, this voltage is permitted a maximum deviation of 10% [32][14].

There are two standard voltages used in the DC-bus: 380 V and 400 V with a 10% deviation[30]. The voltage bus of 400 V has been chosen over the 380 V to ensure a higher voltage than the car's battery and make the charging possible. With this in mind, this design considers that the most suitable option is to use the 400 VAC from the grid i.e use all three phases from the local distribution network.

Solar Panels

The PV module considered for this design has the following characteristics: Model: SunPower Maceon 3, SPR-MAX3-390 Efficiency: 22.6% Nominal power: 390 W Rated Voltage: 64.5 V Rated Current: 6.05 A Area: 1.7 m^2 The area to be covered with the solar panels is the average area of the roof in the petrol station: 150 m^2. That means that we can fit a maximum of 88 solar panels.

The arrangement of the PV modules will be based on the type of converter being used and its limitations. In most of the studied use case scenarios, the PV arrangement comes accompanied by what is known as an MPPT. This ensures that the most power is collected. The power converter used in tandem with the MPPT is a boost converter. Having the just mentioned in consideration, the arrangement of the PV modules will be such that its series voltage does not exceed the 400 VDC of the Microgrid's bus. That results in a maximum of 6 solar panels in series. Given that we can use 88 solar panels that means that we can connect 14.6 rows, rounding down to 14 rows. To sum up, the PV module arrangement has the following characteristics:

- The number of Solar Panels: 84
- PV modules in series: 6
- PV modules in parallel: 14
- Maximum Nominal Series Voltage: 387 Vmpp
- Maximum Nominal Parallel current: 84.7 Ampp
- Maximum output power: 32.8 kW

7.4.4 Power Converters

According to the current block diagram presented in figure 7.2, we will need a total of 5 power converters. Below I will attempt to describe the possible alternatives for each of these power converters and choose the topology that best suits our purpose.

AC/DC: From the Grid to the DC-bus

Given the variable nature of the Solar Panels, the grid will be used to maintain the constant voltage of the DC-bus. Thus, the power converter should be driven with the voltage control method.

As mentioned in section IV, the simplest configuration to use for a three-phase input signal is a 6-pulse rectifier. Nonetheless, the simplicity of the converter has as a consequence a higher Total Harmonic Distortion (THD). This can lead to higher losses on cables, capacitors, and cause electromagnetic interference.

The most common solution found in literature was the stacking of 6-pulse rectifiers either in series or in parallel in order to obtain 12-pulse, 18-pulse, and so on, rectifiers. These new configurations result in a significant decrease in Harmonic Distortion, yet not enough to meet the IEEE 159 standard which requires less than 10% THD for industrial purposes and less than 5% in general applications such as an office building [33] [3].

Further studies have been done on the 12-pulse rectifier to reduce the THD. One approach is to place an auxiliary voltage supply that generates square pulses with a frequency 6 times higher than the line voltage in between the two 6-pulse rectifiers. This has as objective to shape the input current. This leads to a THD of less than 5% at full load [3]. Thus, a 12-pulse rectifier with auxiliary voltage supply is used in this design. The schematic is shown in figure 7.3.

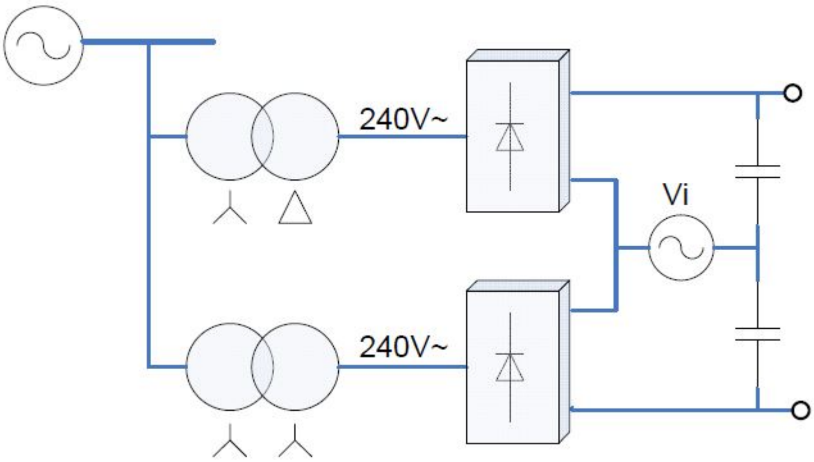

Figure 7.3: 12-pulse rectifier with Auxiliary Voltage Supply to Shape Input Current[3]

DC/DC: From the PV modules arrangement to the DC-bus

As already mentioned in the design of the PV module array, the power converter to be used is a boost converter driven by an MPPT. It is worth remarking that the MPPT is using the current control method which aims to collect the maximum output power. In addition, It should be considered whether the boost converter should be isolated or non-isolated. The non-isolated type is particularly useful to avoid leakage current due to the capacitance between cables and ground. It also allows for higher voltage gains. The downside is the high implementation costs it has [34].

Taking into account the high efficiency of a DC-DC converter between a DC system and the solar panes (97%), the leakage current can be considered to be insignificant. Furthermore, different architectures for the non-isolated boost converter have been developed to allow for higher voltage gains while keeping the costs low. Some examples are the interleaved boost converter or cascaded voltage multiplier cells [34] [21]. Thus, a non-isolated boost converter will be chosen for this design.

DC/DC: From the DC-bus to the ESS and vice versa

The role of the Energy Storage System varies depending on the design. In section IV the ESS has been used for the following purposes:

- Power peak shaving
- DC-bus voltage stabilization
- Full autonomy of the microgrid
- Provide ancillary services to the grid

All these roles inherently involve a bidirectional flow of power, from the DC-bus to the battery and vice versa, or in the case of the ancillary services from the grid to the battery through the DC-bus and vice versa. To this end, two types have been studied: half-bridge buck-boost and three-level buck-boost converter. The conclusion is that the thee-level buck-boost is superior because of the following reasons [3]:

- The voltage stress of the switches and diodes is half.

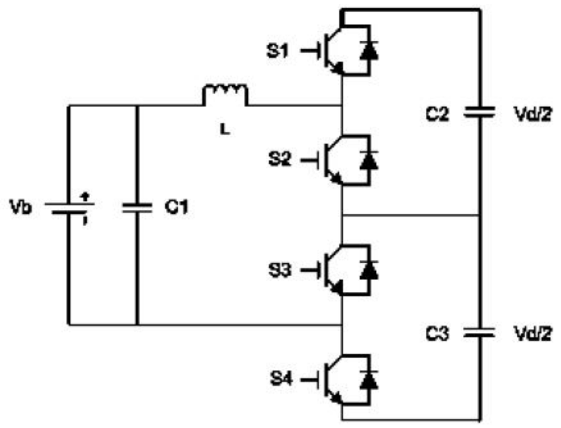

Figure 7.4: Three-level bidirectional Buck-boost Power Converter[3]

- The switching frequency can be lower
- Inductor size can be 3 times smaller
- Higher efficiency in both boost and buck mode.

Thus, this design will consider a three-level buck-boost converter to interface the DC-bus with the ESS. The schematic is shown in figure 7.4

DC/DC: From the DC-bus to the charging station

In order to charge the battery of the EV, the voltage level of the charging station should be higher than that of the car. However, it should not be too high or it would overheat the battery and ultimately damage it. Most of the EVs considered for this research have a voltage battery in the range of 350 to 375 V, which matches nicely with the chosen bus voltage of 400 V. Nevertheless, there are a couple of outsiders which need to be considered: Volkswagen e-Golf: 323 V, Renault Zoe: 400 V, Jaguar I-Pace: 390 V.

The Volkswagen e-Golf represents the lowest battery voltage. The 400 V of bus voltage is about 124% of this value. This does not represent a damaging value for the battery if we consider the common charging voltages used for lithium batteries: $\approx$ 120% [35].

On the other hand, the Renault Zoe and Jaguar I-pace do represent an issue given that their battery's voltage comes very close to the bus voltage making the charging not function properly. A boost converter is required to address this issue. Given that in this case a constant voltage is required at the output, the voltage control method will be used to drive the power converter. The main objective will be to adjust the output voltage to be 120% of that of the battery being charged.

DC/AC: From the DC-bus to the charging station

The last converter to be considered is a DC to AC converter. According to desk research, this feature is not strictly required given that all 10 models being considered also have the possibility of DC-fast-charging. Nevertheless, for completeness and also to allow for the possibility of charging cars outside the ones considered in this report which might not support DC-charging. A DC-AC power converter design will be suggested.

Based on the information collected in section IV the control method to be used will be Pulse Width Modulation. It is worth remarking that all DC-DC converters are technically

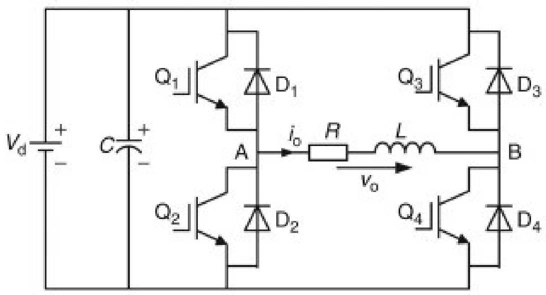

Figure 7.5: Full-Bridge Inverter without a resonant network[4]

controlled using PWM, however, for such converters the variation of the duty cycle results in a higher or lower output voltage. For the inverter the PWM does not control the voltage level, it controls the shape of the output signal. The inverter as such is composed of high-frequency switching devices such as MOSFETS. Typical configurations are the half-bridge and full-bridge inverter. The full-bridge inverter is preferred because, among other reasons, it outputs the same amplitude as the inputted DC voltage. An example schematic of this configuration is shown in figure 7.5. Lastly, as already explained, a resonant network is beneficial in order to perform soft switching. The exact configuration is left to the reader [22] [36].

Table 7.3 summarizes all the theory presented above. It shows the typologies chosen for each power converter, its location in the DC-Microgrid and control method. For a more detailed description of the typologies or the control method, refer to chapter 5.

Table 7.3: Summary of the typologies, locations in the Microgrid and control method of each Power Converter

Type of Conversion	**Typology of Converter**	**Interconnects in the System**	**Control Method**
AC-DC	12-pulse rectifier + AVS	The Grid to the DC-bus	Voltage Control Method
DC-DC	MPPT + Boost Converter	The Solar Panels array to the DC-bus	Current Control Method
DC-DC	Three-level bidirectional + Buck-Boost Converter	The DC-bus to the ESS	Voltage Control Method
DC-DC	Boost Converter	DC-bus to the Charging Station	Voltage Control Method
DC-AC	Full Bridge + Inverter	The DC-bus to the Charging Station	PWM Control Method

7.4.5 Energy Storage System

This section will describe the design of the Energy Storage System. To this end, I will firstly choose the type of storage technology to be used. Then, the parameters described in chapter 6 will be used to define its dimensions.

Based on information found in the literature, there are three storage technologies worth exploring for this research project: lead-acid batteries, capacitors, and lithium-ion batteries. The main characteristics of them have been summarized in table 7.4[37].

Table 7.4: Storage Technologies and their characteristics

ESS Technology	Power Range [kW]	Time Time	Overall Efficiency	Power Density Power Density	Energy Density [Wh/kg]	Storage Durability	Self-Discharge (per day)	Lifetime (yr)	Life cycles
Lead-Acid	Up to 20 000	s-h	0.70-0.90	75-300	30-50	min-days	0.1-0.3%	5-15	2000-4500
Li-ion	Up to 10	min-h	0.85-0.95	50-2000	150-350	min-days	0.1-0.3%	5-15	1500-4500
Capacitor	Up to 50	ms-60min	0.60-0.65	100 000	0.05-5	s-h	40%	5-8	50 000

The main advantage of the capacitor is its power density which is superior to the other two technologies being considered. Nonetheless, it lacks almost all other aspects such as energy density, storage durability, and self-discharge. It is considered that its utility is too specific and will only result in an increase of inefficiency for the system. With this information in mind, it is clear that the most suitable type of storage technologies to be used are the Lead-acid battery and the Li-ion battery. For this design, the lithium-ion battery has been chosen because they have a higher energy density which allows for a much more compact design and it is able to maintain a relatively constant voltage through its discharging process at different discharging rates [38].

Now, let us describe the rest of the parameters to design the ESS as suggested in Chapter 6.

Load demand:

In section 7.4.2 we concluded that the mean load energy demand is 30 kWh if we consider a single charge, and 150 kWh if consider the average number of cars that come to a charging station in a day. The following calculations will be done considering a single charge. The main purpose of the ESS in this report is to do what is known as peak-shaving. In essence, any energy demand that surpasses the mean will be covered by the power provided by the ESS. According to the simulation carried out in MATLAB the maximum excess of energy demand, is approximately 55 kWh. Thus, for a 100% rate of satisfaction, this should be the capacity of the ESS. This will result in a total required capacity of 275 kWh which is far from optimal and its high price can be unacceptable. Thus, to address this issue, the mean of the excess energy required will be used instead. To that end the following steps were taken, the complete code is presented in Appendix A:

- We will reuse the sequence with 1000 values of energy demand generated in 7.4.2. Each value of the sequence will be subtracted from the calculated mean energy demand.
- Any value that is negative, meaning that the energy demand is less than the mean energy demand will be counted as zero.
- This results in a sequence with 1000 values that represent either the excess of energy demand else they are zero. We will calculate the mean of this sequence. This is the mean of the excess energy demand. The ESS will cover this demand.

According to the calculated value, the mean energy demand is 15 kWh. This is almost 4 times smaller with a relatively small decrease in the satisfaction percentage: 85%.

Solar Potential Area:

For The Netherlands, the average solar irradiation is between $2.31 - 2.78\frac{kWh}{m^2}$ per day. The specific photovoltaic power output ranges from $2.73-3.06\frac{kWh}{kWp}$ [39]. It is evident that with the limited available area, the solar panels alone are not capable of fullfilling the demand.

Desired hour of Energy autonomy:

This report has chosen 1 hour to be a reasonable time to charge your EV to 100%. Considering that on average 5 EVs will come to the charging station, the required time for the battery to be functioning is 5 hours. The thought process to choose 1 hour will be described in section 7.4.6.

Allowed depth of discharge:

An acceptable DoD for a lithium-ion battery is 80%. This value will be slightly changed when determining the discharge rate.

C-rate:

Considering that the battery should be able to output 15 kW during five hours and still keep 20% of its total capacity, thus the required total capacity will be 93.75 kWh. For a practical or commercial value, it will be rounded up to 100 kWh. This modifies the DoD to be 75%. And, the discharge rate will be 3/20 = 0.15 C

7.4.6 Load Power Demand

Now that we have determined what will be the energy demand, we can determine the target time in which the energy will be delivered and calculate the power required to do so. Having in mind that the Microgrid being designed in this report will be treated as the replacement of a gas station, the waiting time should be somewhat comparable. Nevertheless, this is thought to be a wrong approach. It has to be recognized that we are dealing with completely different transportation technologies.

A typical fueling time is of around 5 minutes. It is not logical to expect a similar time to charge an EV without having consequences such as damaging the battery. On the other hand, it is also not realistic to expect customers that come to charge their EV to wait for 3 or more hours. In this report, one hour is considered as a reasonable time to wait for a full charge. This decision also makes the power calculations much easier. This because to calculate the power required given a certain energy demand and a time, equation 7.2 can be used. It is easy to see that if we consider the time to be 1 hour, the magnitude of both the output power and the capacity are effectively the same. In our example, we will need an output power of 30 kW in order to deliver 30 kWh in an hour.

$$Ouput\_Power[kW] \cdot Time[h] = Capacity\_of\_the\_battery[kWh] \tag{7.2}$$

From desk research, it was found that every single model of EV considered in this report supports DC charging. If we consider both the mean energy demand (30 kWh) and the mean excess energy demand (15 kWh), the required output power to satisfy this energy demand is 45 kW. The standard output power of 50 kW will be chosen for the fast DC charging this design. 15 kW will be provided by the ESS and 35 kW will be provided by the grid. As it was previously mentioned, the Volkswagen e-Golf and Renault Zoe support a maximum DC charging power of 40 and 46 kW respectively [40]. For these models, the output power will have to be decreased and not damage the batteries. The control method to perform such power variation is left for further research.

The inverter that allows for AC charging can only output a 1-phase AC signal. All models considered in this report allow for an AC charging with an output power of 7.4 kW. Thus, this will be the only considered output power for AC charging.

Chapter 8

CONCLUSION AND FUTURE SCOPE

To sum up, this research project has attempted to evaluate and propose the best approach for the electrification of a gas station as a solution to the massive insertion of Electric Vehicles. It should first, consider alternatives such as the insertion of renewable resources for power generation to reduce its environmental impact. Second, the technology involved should be mature enough to be reproducible and avoid scarcity among users, especially for the ones who make a living out of the transportation sector. Third, it should consider the technical limitations of the current electrical network in addition to limiting its use as much as possible.

This report described a possible solution to address these matters: a DC-microgrid. This distribution network was found to be one of the best alternatives for the future of energy distribution because of several reasons. Firstly, it allows for a mixture of operational states. It can work in tandem with the grid as well as in complete isolation from it. This flexibility makes easier its adoption whether it is in a metropolis or a remote island with no proper electrical infrastructure. In this design that feature was exploited by using the grid as a complementary energy resource for the Microgrid. Second, it allows for the insertion of Distributed Energy Resources. In our particular case, the alternative sources of energy considered are solar panels. Third, the DC-microgrid is superior to the other architectures because fewer energy transformation steps required. This is true for the interfacing between the DC-bus and the chosen DER, ESS, and DC loads. Lastly, this solution offers easier controllability of power flow and level which is beneficial for safety reasons. This increased safety also allows for a higher output power which with the advancement of battery technologies will result in a much faster charging time

The main contribution of this writing is on the detailed and structured design offered in the use case scenario. The resulting design not only described typologies to be used in the Microgrid but also presented concrete energy and power values. For the DC fast charging, it was established that 50 kW is the most optimal output power. This ensures to charge the considered EVs in one hour or less 88% of the time. All EV models support DC charging, however, two cannot support the 50 kW. For this, the design also includes AC charging with an output power of 7.4 kW which can be supported by every EV model considered. On average the charging station has the capability of satisfying the energy demand of five Electric vehicles per day. This means that it should be able to deliver 250 kWh per day out of which 175 kWh will be supplied by the grid and PV cells and 75 kWh will be supplied by the 100 kWh Energy Storage System. The process to obtain these results has been described in a recipe manner and can easily be re-used for a different application since each decision was described and backed up in detail. That being said, the time constraint of this research project did not allow for more practical results such as modeling and simulation of the microgrid. Furthermore, key aspects required for the completeness of the design such as the elaboration of the control method in each power converter, or the modeling of power losses due to transmission lines, were not covered in this report.

In spite of the fact that extensive research has been done in the area of Microgrids, it is thought that a lot is left to be done in the practical aspect. Some of the recommendations for further research involve the following. First, more experimentation on the combination of the grid and renewable resources to see their exact interaction at an electrical level. Second, the evaluation of the ideal locations for the proposed solution. It was suggested that the current locations of the gas stations might not be ideal due to the lack of proper grid infrastructure. Lastly, experimentation with alternative and innovative configurations of power converters in DC-microgrids.

Appendix A

MATLAB CODE FOR CALCULATION OF ENERGY DEMAND AND EXCESS ENERGY DEMAND

```
clear all;
close all;
s = RandStream('mlfg6331_64')

%% generating sequence according to probability

%Sequence of numbers for the SoC
SoC_seq = datasample(s,[10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 ...
    85],1000,'Weights',[0.01 0.09 0.01 0.04 0.14 0.04 0.1 0.09 0.1 ...
    0.09 0.1 0.09 0.03 0.04 0.01 0.01]);
%calculated the mean and std of generated sequence
SoC_mean = mean(SoC_seq);
SoC_med = median(SoC_seq);
SoC_std = std(SoC_seq);


%Sequence of nembers for the battery capacity
Bat_seq = datasample(s,[47.5 95 36 32 64 37.9 52 64 95 ...
    84.7],1000,'Weights',[0.323 0.127 0.096 0.089 0.076 0.067 0.066 ...
    0.061 0.052 0.043]);
Bat_mean = mean(Bat_seq);
Bat_med = median(Bat_seq);
Bat_std = std(Bat_seq);


%% Combining Battery Capacity with State of Charge

SoC_decimal = SoC_seq/100;
multiplier = 1 - SoC_decimal;
rand_demand = Bat_seq .* multiplier;
mean_demand = mean(rand_demand);
minimo = min(rand_demand);
maximo = max(rand_demand);
s1 = length(find(rand_demand < 50)); % count less than threshold
s2 = length(find(rand_demand > 50)); % count greater than threshold


%% Obtaining excess of energy required
excess = rand_demand - mean_demand;
```

```
excess = max(excess,0);
max_excess = max(excess);
mean_excess = mean(nonzeros(excess)); %obtaining mean and ignoring ...
    zero values
                                           %this is also the required ...
                                               power for
                                           %the battery as well as the energy
                                           %demand since we are using the rate
                                           %of charge 1C.
median_excess = median(nonzeros(excess)); %obtaining mdeian and ...
    ignoring zero values

%% obtaining percentage of fulfilled demand
%test = (mean_demand + mean_excess) - rand_demand; %generated energy ...
    - required energy
test = (50) - rand_demand; %generated energy - required energy --> ...
    only fulfilling standard
%test = (62.5) - rand_demand; %generated energy - required energy --> ...
    considering extra demand to increase satisfaction
fulfilled_percentage = (nnz(test ≥ 0))/10; %count when generated ...
    energy was enough

%for 90,80,70% of SoC
Ninety = rand_demand * 0.9;
test = (50) - Ninety; %generated energy - required energy --> only ...
    fulfilling standard
fulfilled_percentage_90 = (nnz(test ≥ 0))/10; %count when generated ...
    energy was enough
Eighty = rand_demand * 0.8;
test = (50) - Eighty; %generated energy - required energy --> only ...
    fulfilling standard
fulfilled_percentage_80 = (nnz(test ≥ 0))/10; %count when generated ...
    energy was enough
Seventy = rand_demand * 0.7;
test = (50) - Seventy; %generated energy - required energy --> only ...
    fulfilling standard
fulfilled_percentage_70 = (nnz(test ≥ 0))/10; %count when generated ...
    energy was enough

%% plotting results
figure(1);
plot(1:1000, Bat_seq);
xlabel('Samples');
ylabel('Battery Capacity [kWh]');
title('Battery Capacity Acoording to Probability');

figure(2);
plot(1:1000, SoC_seq);
xlabel('Samples');
ylabel('State Of Charge [%]');
title('State of Charge Acoording to Probability');

figure(3);
x = 1:1000;
plot(x, rand_demand, 'DisplayName','Energy Demand');
hold on;
plot(x, ones(size(x))*mean_demand,'Linewidth', 2, 'Color', ...
    'r','DisplayName','Mean E demand');
```

```
xlabel('Samples');
ylabel('Energy demand [kWh]');
title('Energy Demand Acoording to Probability');
legend


figure(4);
plot(x, excess, 'DisplayName','Excess Energy Demand');
hold on;
plot(x, ones(size(x))*mean_excess,'Linewidth', 2, 'Color', ...
    'r','DisplayName','Mean E demand excess');
hold on;
plot(x, ones(size(x))*max_excess,'Linewidth', 2, 'Color', ...
    'g','DisplayName','Max E demand excess');
xlabel('Samples');
ylabel('Excess Energy demand [kWh]');
title('Excess Energy Demand Acoording to Probability');
legend
```

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