Smart TinyLab voor Systeemintegratie in de Bouw

Rapportage WP 6

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Voorwoord

Het *Smart TinyLab voor systeemintegratie in de bouw* is een lab waarin bouwpartners en bouw gerelateerde bedrijven hun producten in de praktijk kunnen ontwikkelen, testen, valideren en demonstreren. De doelstelling van het gelijknamige EFRO project (PROJ-00937) is de exploitatie van het Smart TinyLab. Ter uitwerking van die doelstelling zijn zes werkpakketten gedefinieerd:

WP 1: Smart TinyLab
WP 2: Dynamische prestatie monitoring van houten gevelelementen
WP 3: Glas als actieve warmteregulator
WP 4: Sensing en monitoring
WP 5: Data informatiediensten
WP 6: Gelijkstroomgrid

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In de onderhavige rapportage worden de resultaten van diverse onderzoeken uitgevoerd voor werkpakket 6, behandeld. De volgende personen en organisaties hebben bijgedragen aan dit werkpakket en de resulterende onderhavige rapportage:

Saxion Hogeschool
Academie Business, Building & Technology (BBT)
Lectoraat Sustainable Building Technology (SBT)
Lectoraat Sustainable Energy Systems

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Abbreviations

RES	Renewable Energy System
LV	Low Voltage
DR	Demand Response
ESS	Energy Storage Systems
DC	Direct Current
AC	Alternating Current
LVDC	Low Voltage Direct Current
HVDC	High Voltage Direct Current
EU	European Union
SBT	Sustainable Building Technology
PV	Photovoltaic
P2P	Peer-To-Peer
CHP	Combined Heat and Power
OCR	Over Current Relay
DG	Distribution Generators
CPL	Constant Power Load
PoE	Power over Ethernet
V1G	Unidirectional controller charging
V2G	Vehicle-To-Grid
V2H/B	Vehicle-To-Home/Building
I	Current
AFE	Active Front End
IGBT	Insulated Gate Bipolar Transistors
THD	Total Harmonic Distortion
PWM	Pulse Width Modulation
CBB	Cascaded Buck-Boost
DAB	Dual Active Bridge
TAB	Triple Active Bridge

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Management Samenvatting

Om de opwarming van de aarde tegen te gaan door de vermindering van koolstofemissies, moet de mensheid overschakelen van het gebruik van energiebronnen op basis van fossiele brandstoffen naar hernieuwbare energiesystemen (RES), die vanwege de weersomstandigheden meer onderbroken zijn. Als gevolg van deze omschakeling zullen veel belastingen die traditioneel bijna uitsluitend werden aangedreven door fossiele brandstoffen, zoals auto's en huishoudelijke verwarming, in toenemende mate elektrisch worden aangedreven door hernieuwbare bronnen via het elektriciteitsnet. Bovendien wordt er meer energie opgewekt in lokale laagspanningsnetten (LV). Deze decentralisatie van het elektriciteitsnetwerk, waarbij energiebronnen dichter bij de eindgebruiker worden gebracht, is iets waarvoor het netwerk niet is ontworpen, aangezien traditioneel een gecentraliseerde structuur voor energieopwekking bestond.

Deze veranderingen leiden tot vele problemen in de transmissie- en distributienetten, aangezien de huidige netwerkinfrastructuur niet voldoende is om het inherente verschil tussen energievraag en -opwekking in evenwicht te brengen. In Nederland is dit een zorgwekkend onderwerp, aangezien het elektriciteitsnetwerk steeds meer overbelast raakt, waarbij nieuwe RES-projecten en residentiële en commerciële belastingen moeten wachten om op het net te worden aangesloten. Er moeten maatregelen worden genomen om zowel de voortgang van de Energietransitie te waarborgen als de continuïteit van de energievoorziening te garanderen. Flexibiliteit, het vermogen van een elektriciteitsnetwerk om energieproductie en energievraag in balans te brengen, moet worden vergroot in het elektriciteitsnetwerk. Opties om de flexibiliteit te vergroten zijn onder meer versterking van het elektriciteitsnet, de controle van verplaatsbare belastingen via vraagrespons en de integratie van energieopslagsystemen (ESS) in het netwerk . Een benadering om al deze opties te faciliteren, is de integratie van gelijkstroom (DC) -gebaseerde elektriciteitsnetten in het huidige wisselstroom (AC) -gebaseerde elektriciteitsnet.

Op dit moment worden voornamelijk wisselstroom (AC) elektriciteitsnetwerken gebruikt, met name voor het creëren van laagspanningsnetwerken. Veel commerciële instellingen en beleidsmakers heroverwegen echter de rol die laagspanningsgelijkstroom (LVDC) netwerken kunnen spelen om de Energietransitie mogelijk te maken. Het Nederlandse bedrijf DC Systems leidt deze herwaardering, samen met bedrijven zoals Eaton, Microgrid Solutions en Baas B.V., evenals non-profit stichtingen zoals Current/OS. Het is daarom essentieel dat er meer toegepast onderzoek wordt uitgevoerd om het gebruik van LVDC-netwerken te evalueren. Hiervoor zijn praktische faciliteiten nodig. Bovendien zijn onderwijsfaciliteiten nodig om studenten de mogelijkheid te bieden zowel de theoretische als praktische aspecten van DC-technologieën en -systemen te verkennen. Smart Tinylab WP6 biedt mogelijkheden voor onderzoek en onderwijs. Het doel van WP6 is om een werkend LVDC-netwerk te onderzoeken, te ontwikkelen en te testen in de Smart Tinylab. De subdoelen en resultaten van de subdoelen zijn als volgt:

(I) Het realiseren van een praktisch laboratorium voor het testen van een lokaal DC-netwerk en nieuwe DC-componenten in een gebruikerssituatie, en de mogelijkheid om de prestaties van een DC-netwerk met DC-apparaten te vergelijken met een AC-netwerk met AC-apparaten.

Het praktische laboratorium van Tinylab werd gerealiseerd zoals beschreven in Hoofdstuk 6. Het laboratorium heeft de mogelijkheid om de prestaties van DC- en AC-netwerken te vergelijken met een aantal relevante apparaten.

(II) Inzichten verkrijgen uit het laboratorium met betrekking tot technische prestaties, gebruikerservaringen en veiligheidsaspecten van DC-netwerken in vergelijking met AC-netwerken voor verdere ontwikkeling.

Helaas was er door vertraging bij de bouw van het DC-netwerk in Tinylab geen praktische test mogelijk met betrekking tot prestaties, gebruikerservaringen of veiligheid binnen de projectperiode. Er werd echter wel technische prestatie en veiligheid onderzocht in de literatuur (zie Hoofdstukken 2, 3 en 4), waardoor we veel inzicht kregen in de werking van DC-netwerken. Bovendien biedt dit ons een startpunt voor toekomstig praktijkonderzoek met Tinylab.

(III) Bijdragen aan de (inter)nationale kennis en ervaring met DC-netwerken voor woningen en kantoorgebouwen.

De kennis en expertise die tijdens dit project zijn opgedaan, zijn gunstig voor de ontwikkeling van DC-netwerken in Nederland. Dit omvat zowel DC-netwerken in het algemeen als specifieke toepassingen voor woningen. Dit heeft twee voordelen. Ten eerste hebben onderzoekers in zowel de industrie (het projectconsortium) als bij Saxion nu een beter begrip van de werking van DC-netwerken en hun mogelijke toekomstige toepassingen. Dit leidt ertoe dat DC-netwerken worden overwogen als haalbare oplossingen binnen toekomstige projecten. Ten tweede zijn onderzoekers en docenten bij Saxion nu in staat om meer over DC-netwerken op te nemen in het curriculum. Dit stelt studenten van Saxion, met name op de afdeling Elektrotechniek en Elektronica, in staat om meer te leren over DC-netwerken en deze kennis mee te nemen in hun toekomstige carrières, waardoor er in de toekomst meer DC-netwerkprojecten kunnen worden overwogen.

(IV) Bijdragen aan de ontwikkeling van componenten en marktproposities van partners (leveranciers van DC-componenten, DC-installatiebedrijven) door middel van praktisch onderzoek.

Net als bij doel II is door gebrek aan tijd voor praktisch onderzoek dit doel niet bereikt. Echter hebben de uitdagingen bij de installatie van het DC-netwerk in Tinylab Eaton en Microgrid Solutions geholpen bij het vergroten van hun kennis over DC-netwerken. Op dit vlak is het doel bereikt.

Bovendien werden een aantal onderzoeksvragen gesteld. Hieronder volgen korte samenvattingen van elke vraag:

1. *Welke actieve controle is mogelijk voor DC-netwerken?*

Actieve controle is mogelijk door het gebruik van gecontroleerde vermogenselektronica in DC-netwerken. Hierbij zijn Actieve Front Ends (AFE) kritisch voor de AC/DC-netwerkaansluiting. Bovendien kunnen DC-netwerken zowel in een verbonden netwerk als in een geïsoleerde modus werken, waarbij vermogen al dan niet (tijdelijk) wordt uitgewisseld met een verbonden (vaak AC) netwerk. Ten slotte werden verschillende netwerkregelstrategieën onderzocht, waaronder gecentraliseerde, gedecentraliseerde, gedistribueerde en hiërarchische. Current/OS werd besproken als een voorbeeld van een in Nederland ontwikkeld protocol dat momenteel op de markt is.

2. *Welke componenten en technieken zijn nodig om een LV DC-netwerksysteem te hebben dat kan worden aangesloten op een bestaand AC LV/MV-netwerk?*

Vermogenselektronica zijn cruciale componenten in LVDC-systemen. Deze omvatten gelijkrichters (AC/DC), omvormers (DC/AC) en verschillende soorten DC/DC-omzetters, waaronder buck, buck-boost en de veelgebruikte Dual Active Bridge (DAB) omzetter in DC-netwerken. Bovendien zijn opslag, energieopwekking en/of netwerkaansluitingen vereist. Opslag is nodig om de flexibiliteit van het systeem te vergroten en eventuele onevenwichtigheden in vermogen te balanceren. PV is nodig voor een inheemse DC-stroomvoorziening, terwijl een aangesloten elektriciteitsnetwerk, meestal AC, ook kan worden gebruikt. Ten slotte zijn er belastingen die direct in DC kunnen worden gebruikt (zoals computers en magnetrons) of kunnen worden omgezet (zoals de meeste wasmachines).

3. *Welke apparaten die momenteel op de markt zijn, zijn geschikt voor gebruik in een LV DC-netwerk? (AC- en DC-apparaten), en welke apparaten zijn in ontwikkeling?*

Een aantal apparaten bleek compatibel te zijn met DC, zie ook het antwoord op vraag 2. Verder zijn er momenteel DC-versies in ontwikkeling voor power over ethernet, elektrisch voertuig (EV)-opladen en meer traditionele AC-huishoudelijke apparaten zoals wasmachines en verwarming.

4. *Wat is de architectuur van een DC-model en hoe kan dit worden opgebouwd?*

Een DC-model werd uitvoerig besproken in Hoofdstuk 5, inclusief de modelvereisten en topologie. Deze architectuur omvat vermogenselektronica, belastingen, energieopslag en zonne-PV-generatie. Het werd geconstrueerd in MATLAB SIMULINK.

5. *Welke AC- en DC-ontwerpen voor huishoudelijke netwerken worden als haalbaar beschouwd?*

Een netwerkontwerp werd gedetailleerder geanalyseerd, namelijk het AC/DC-netwerkontwerp. Dit wordt als haalbaar beschouwd in Nederland, omdat het zowel de behoefte aan vermogensconversies in een huishouden vermindert (alleen DC/DC) als gebruikmaakt van het bestaande AC-netwerk om aan de stroombehoeften van het huishouden te voldoen wanneer de DC-netwerkgeneratie- en opslagmogelijkheden onvoldoende zijn. Het DC-netwerk kan daarom worden beschouwd als een zijnetwerk van het hoofd-AC-netwerk. Bovendien zijn zogenaamde Nanogrids (kleinere systemen binnen een microgrid-infrastructuur) haalbaar in de vorm van DC-garages, DC-verlichting, DC-huisbeveiligingssystemen en indien nodig DC-pompsystemen.

6. *Welke technische uitdagingen, inclusief veiligheid, hebben DC-netwerken?*

Een aantal technische uitdagingen werd onderzocht, waaronder verschillende soorten storingen (aarding, stroom, geen nul doorgang). Bovendien werd de IEC TS 60479-1-2026-norm geanalyseerd. Ook werd de classificatie van gevaren op basis van stroom en spanning onderzocht om vast te stellen wat relevant is voor LVDC.

Samengevat kan worden gesteld dat het doel van WP6 om een LVDC-netwerk te onderzoeken, te ontwikkelen en te testen in de Tinylab gedeeltelijk succesvol was. Hoewel er onderzoek en ontwikkeling zijn verricht en er een functionerend LVDC-netwerk is gerealiseerd, kon het netwerk niet praktisch worden getest, behalve om de juiste installatie te bevestigen. Desalniettemin kan dit project als een succes worden beschouwd, omdat er kennis is opgedaan, de meeste subdoelen zijn bereikt en een aantal relevante onderzoeksvragen zijn beantwoord. Deze informatie is niet alleen nuttig voor onderzoekers, maar ook voor het onderwijzen van studenten. Als belangrijke les voor de toekomstige ontwikkeling van een DC-netwerkproject moet de planning niet te optimistisch worden opgesteld, vooral als onderdeel van een groot project met andere doelen en werkpakketten. Met andere woorden, er moet meer tijd worden genomen voor ontwikkeling en installatie, om voldoende tijd te garanderen voor fysieke tests.

De aanbevelingen voor onderzoek in de toekomst zijn als volgt: Het model vereist herbeoordeling en verdere ontwikkeling. Hoewel er grote stappen zijn gezet bij de creatie van het model, functioneert het nog niet zoals vereist. Verschillende componenten moeten opnieuw worden getest en vervolgens geïntegreerd in het model, terwijl wordt getest of ze correct functioneren. Bovendien moeten de niet-gehaalde vereisten opnieuw worden beoordeeld.

- Het model moet worden gevalideerd in combinatie met de Tinylab-opstelling. De meeste waarden die in het model worden gebruikt, zijn (bijna) ideaal en in de praktijk zullen ze geen nauwkeurige weerspiegeling zijn van de Tinylab om inzicht te krijgen in de functionaliteit ervan. Daarom moeten de real-world componenten die in de Tinylab zijn gebruikt ook nauwkeurig worden gedimensioneerd in het model. Bovendien moet beperking ook worden toegevoegd als een optie voor zowel zonne-PV als bepaalde belastingen, om een nauwkeuriger model te creëren van wat doorgaans kan worden gecontroleerd in actieve microgrids.
- Verder onderzoek naar DC-netwerkregelstrategieën is nodig. Om een beter begrip te krijgen van welke regelstrategieën nuttig zijn in bepaalde situaties, moeten relevante strategieën zowel in het model worden getest (en daarom opnieuw worden gecreëerd in het model) als in de Tinylab zelf. Dit onderzoek moet onder andere Current/OS omvatten, aangezien dit naar verwachting de overheersende strategie zal zijn die in Nederland in de komende jaren zal worden gebruikt.
- Een praktische vergelijking met behulp van de Tinylab tussen AC en DC in verschillende huidige en toekomstige scenario's is nodig. Dit omvat een simulatiestudie. De scenario's moeten zowel residentiële, kantoor- als industriële gevallen omvatten, waarin DC-netwerktechnologie veelbelovend wordt geacht. Hoewel dit rapport als algemene richtlijn kan worden gebruikt om veelbelovende scenario's te evalueren, zou een meer diepgaande analyse vóór de studie nuttig zijn in samenwerking met potentiële DC-netwerkgebruikers.
- Een gedetailleerd praktisch onderzoek naar de gebruikerservaringen met betrekking tot DC-netwerkinteracties is nodig. Dit kan worden gedaan met behulp van de Tinylab. Deze stap is essentieel om de acceptatie van DC-netwerken in huishoudens te meten en specifiek te onderzoeken welke barrières voor acceptatie door gebruikers moeten worden overwonnen voordat een bredere uitrol haalbaar is in Nederland.
- Als uitbreiding van het punt over gebruikerservaring, is een praktische veiligheidsanalyse van de Tinylab vereist. Dit zou praktisch evalueren welke veiligheidskwesties (indien nog aanwezig) moeten worden aangepakt voordat een bredere uitrol haalbaar is in Nederland.
- DC-grid theorie moet meer volledig geïntegreerd worden in het curriculum van Saxion, met name (maar niet uitsluitend) bij de opleiding Elektrotechniek. Dit moet besproken worden met de

docenten van de relevante vakken, zoals vermogenselektronica, energiesystemen en netwerk gerelateerde vakken. Daarnaast moet de Tinylab gebruikt worden als testomgeving om studenten een praktisch begrip te geven van hoe DC-grids functioneren. Het model kan gebruikt worden om een meer theoretisch begrip te verkrijgen

1 Introduction

To combat the increase in global temperature through the reduction carbon emissions, humanity must switch from using fossil fuel based energy sources to renewable energy systems (RES), which due to weather conditions are more intermittent in nature. As a result of this switch, many loads which were traditionally powered almost exclusively by fossil fuels, such as automotive vehicles and household heating, will increasingly be powered electrically by RESs through the electricity grid. Furthermore, more energy is being generated in local Low Voltage (LV) grids. This decentralization of the electricity grid, which brings power sources closer to the end user [1], is something that the grid was not designed for, as traditionally a centralized structure for energy generation existed.

The aforementioned changes lead to many transmission and distributions grid issues, as the current network infrastructure is not sufficient to balance the inherent mismatch between energy demand and generation. In the Netherlands this is a topic of concern, as the electricity network is becoming increasingly congested, whereby new RES projects, as well as residential and commercial loads, have to wait to be connected to the grid [2]. Actions need to be taken to ensure both the continuation of the energy transition while guaranteeing continuity of supply [3].

Flexibility, the ability of an electricity network to balance energy production and demand, needs to be increased in the electrical grid. Options to increase flexibility include electricity grid reinforcement, the control of time shiftable loads through Demand Response (DR) as well as the integration of Energy Storage Systems (ESS) into the grid [4]. One approach to facilitating all of these options is through the integration of Direct Current (DC) based electricity grids into the current Alternating Current (AC) based electricity grid [5].

1.1 Background

This chapter presents background knowledge about DC grids. First, the history of DC grids is discussed. Next, an overview of previous LV DC grid projects is shown. Finally, an introduction into the reasoning behind the Smart Tinylab Grid design is discussed.

1.1.1 The changing role of DC grids

Currently, AC is the dominant power distribution technology. The dominance of the AC grid goes back to the 19th century after the so-called “War of Currents”. The outcome of the rivalry between Thomas Edison, inventor of DC, and George Westinghouse, a pioneer of the electricity network , would determine which technologies were used to build the foundations of the electric grid we use today. During their dispute, Edison was a proponent of DC grids while Westinghouse championed AC grids with the support of Nikolas Tesla, an AC grid innovator. Transformers made AC the winner of the dispute, as at the time no device could step up or set down the voltage of DC [6]**.** Therefore, DC voltage could not be stepped up to a higher voltage, meaning that DC electricity couldn’t be transported long distances without major losses.

Nonetheless, many are reevaluating the usage of DC grid technology for two reasons. First, DC-DC converters are available on the market and, due to advances in power semiconductors and integrated circuits since the 1970s, are more economically viable than before [7] .As a result, DC systems can be found today in several applications such as telecommunication, electric vehicles, ships, traction systems and high voltage DC (HVDC) [8]**.** Secondly, the loads which typically are integrated into electricity grids, often LV grids, are DC based. The consumption loads include lighting, USB-based appliances, laptops and heating solutions such as heat pumps (see also Section 3.4)[9]. Furthermore, both PV and battery systems such as lithium-ion batteries, which are DC based, are being integrated into the electricity network. This decentralization of the electricity system is an important part of the energy transition, specifically to enable more renewables can be integrated.

Although the current AC grid is a proven concept, the question is raised as to why LVAC grids are still prevalent while, in many cases, DC electricity is being produced, consumed and stored. As a results, is it possible that more power conversions occur than is strictly necessary. A clear example of this is shown in Figure 1, where both an AC and a DC building are shown [10]. To supply to the loads, the current needs to go under a conversion to meet the requirements of the AC microgrid and then convert back again to DC to meet with the requirements of the loads that are DC-based. However, in the case of the DC building, this redundant conversion is eliminated avoiding conversion losses but more DC/DC conversions are needed. Power conversion is discussed in more detail in Section 2.2.

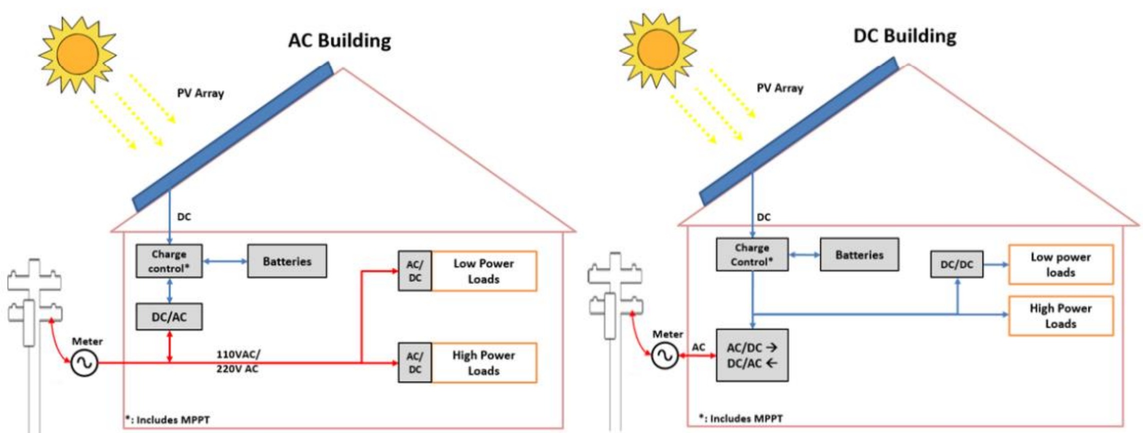

Figure 1. AC residential distribution system and the equivalent DC system [15]

In that context, DC grid households with relatively high PV production, with an ESS and a number of DC-based devices, should have fewer losses when compared to the same household with only an AC grid. Figure 2 illustrates the spectrum of electric savings percentages in relation to an AC-powered household, derived from the DC electric savings estimates [11]:

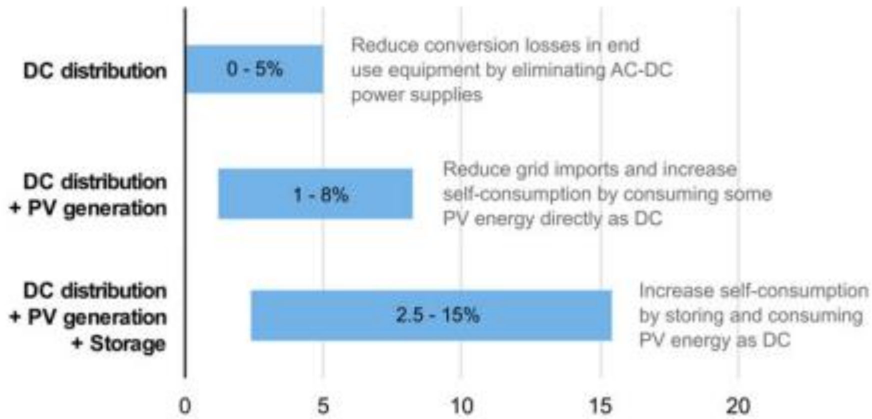

Figure 2. Percent of Electric Savings when Compared to Equivalent AC Home [11]

The imagine not only show the potential electric savings but it also highlights how the introduction of PV and batteries can enhance self-consumption and decrease the reliance on the grid. However, it is important to note that DC microgrids can also potentially offer significant benefits to AC microgrids by exporting their excess produced energy. DC microgrids can play role in balancing AC microgrids by addressing production-consumption mismatches, which is studied in Chapter 5.

1.1.2 DC grid projects

The European Commission has actively engaged in exploring the potential of low-voltage DC technologies to accelerate the transition towards cleaner energy sources [12]. In line with this objective, the Commission is conducting investigations to assess the benefits and implications of integrating such technologies into the energy landscape. Drawing insights from these findings, the European Commission intends to collaborate with European and international standardization bodies to establish the required standards and protocols. Through these efforts, the European Union (EU) is actively encouraging the adoption and implementation of DC technologies as part of its broader initiative to promote sustainable energy solutions. In fact, there is currently an European initiative called "High Voltage Direct Current & DC Technologies" that has the objective to bring together stakeholders of the energy sector to accelerate the integration of renewable energy sources in Europe [13].

In this context, many European countries have begun to invest in DC research projects. The following are some examples:

- DC-Flexhouse:

The Zuyd University of Applied Sciences in the Netherlands is leading this project with the objective of developing a method for replacing the energy infrastructure in homes introducing DC technology. The ultimate goal is to establish a plug-and-play installation approach offering an alternative to conventional renovation projects in terms of cost-effectiveness and reduced lead time [14]. In order to incentivize homeowners and companies to adopt this approach, the project provides a comprehensive cost analysis for transitioning from AC technology to DC technology in residential households. The aim is to offer valuable insights into the financial implications of such a replacement, allowing stakeholders to make informed decisions based on the potential cost savings and benefits associated with implementing DC systems. On top of that, this project studies the integration and use of renewable energy sources, the energy efficiency in homes and offices and the controllability of the energy flows in homes. The following questions are investigated during the project [15]:

-How can we use an existing AC installation to include DC techniques?
-What is needed to make a DC system as safe or safer than AC?
-What AC appliances can easily be converted to DC?

- Components and interfacing for AC & DC side protection system – AC & DC grid: components and systems for grid optimization:

The primary objective of this project is to develop protection strategies that facilitate the optimal architecture of both AC and DC systems within the grid. Additionally, the project aims to explore innovative power electronic-based technologies that can effectively address congestion issues by enabling power injection from decentralized energy systems to centralized ones. Furthermore, the project will investigate various aspects such as load shifting to optimize power flows, strategies to avoid grid reinforcement, and the design of protection systems for high-voltage direct current (HVDC) grids [16].

- Converting Data Centers in Energy Flexibility Ecosystems (CATALYSTS)

The CATALYST project aims to address the challenges faced by data centers, which are significant energy consumers due to increasing digitization. By integrating RES and improving energy efficiency, the project aims to reduce the carbon footprint of data centers while enhancing their security and resilience against climate change. Existing and new data centers will be transformed into flexible multi-energy hubs, offering mutualized flexibility services to smart energy grids, all in the DC domain [17].

Developing countries with a significant number of rural areas adopt a different approach, prioritizing the electrification of these regions. It is estimated that 70% of the population of India lives in rural areas and only 56% of rural households have access to electricity [18]. Therefore, the integration of renewable energies into a DC microgrid is discussed in articles such as [19], focused in operation and control strategies, [18], which gives a Zero Energy Building overview or [20], that discusses a cost-effective and reliable solar-based microgrid.

1.2 Description of the WP 6 tasks

Currently, AC electricity grids are primarily used, especially to create LV grids. Many commercial institutions and policy makers are revaluating the role LVDC grids can plan to enable the energy transition. Dutch company DC Systems [21] is spearheading this revaluation, with companies such as Eaton [22], Microgrid Solutions [23] and Baas B.V. [24], as well as non-profit foundations such as Current/OS [25]. As a result, it is critical that more applied research be conducted to evaluate the use of LVDC networks. To do this, practical facilities are needed. Furthermore, within education facilities are needed allow students to engage with both the theory and the practical aspects of DC technologies and systems. Smart Tinylab WP6 enables opportunities for research as well as education.

The goal of WP6 is to investigate, develop and test a working LVDC grid in the Smart Tinylab. This is split into 4 subgoals (taken from the original project proposal):

(I) To realize a practical laboratory for testing a local DC grid and new DC components in a user situation and the ability to compare the performance of a DC grid with DC devices to an AC grid with AC devices.
(II) To gain insights from the laboratory regarding technical performance, user experiences, and safety aspects of DC grids in relation to AC grids for further development.
(III) To contribute to the (inter)national knowledge and experience with DC grids for residential and office buildings.
(IV) To contribute to the component development and market proposition of partners (DC component suppliers, DC installation companies) through practical research.

To achieve these goals and focus our research, a number of question were answered. These are:

1. What active control is possible for DC grids?
2. What are the components and techniques necessary in order to have an LV DC grid system, which can be connected to an existing AC LV/MV grid?
3. Which devices currently on the market are suitable to be used in an LV DC grid? (AC and DC devices), and which devices are in development?
4. What is the architecture of a DC model, and how can this be constructed?
5. Which AC and DC household grid designs are considered feasible?
6. Which technical challenges, including safety, do DC grids have?

1.3 The role of the Smart Tinylab

The Lectoraat Sustainable Building Technology (SBT) has developed the Smart TinyLab, a dedicated testing environment for companies, researchers and students seeking to evaluate equipment and market innovations in the field of energy management and control, alongside other systems and solutions *[26]* . This state-of-the-art lab enables the simulation and evaluation of the impact of indoor and outdoor climate conditions, as well as the energy consumption of various products. By facilitating a comparison between theoretical and practical characteristics, the Smart Tiny Lab offers valuable insights into the real-world performance of energy-related technologies.

WP6 introduces a DC grid to the Smart Tinylab. This is further detailed in Chapter 6. This DC testing environment proves ideal for researchers examining various aspects of DC technology, including safety challenges, renewable energy integration, efficiency comparisons between DC and AC batteries, appliance efficiency, and overall system efficiency. Furthermore, although not within the scope of this project, in future research the role of microgrid control in DC grids can be investigated. This will include the intelligent control of shiftable devices in the Smart Tinylab as well the usage of a storage device, in order to achieve a specific goal. Goals include reducing peak imbalances in a connected AC grid, increasing the lifetime of connected loads such as storage devices, minimizing electricity costs made and minimizing the carbon emissions of the energy used. More on control is presented in Section 3.

1.4 Report Outline

The following chapters are structured as follows:

- Chapter 2 investigates the background and architecture of DC grid systems, including grid components which include producers, consumers and power electronics. Furthermore, control of DC grids is examined, as well as the challenges encountered when implementing DC grids. Research questions 1, 2, and 6 are examined specifically.
- Chapter 3 looks at DC grid designs, focusing on hybrid AC/DC grid designs. Research question 5 is answered in the combination of both chapters.
- Chapter 4 looks at DC grid devices which can be implemented on a household level. Research question 3 is answered.
- Chapter 5 shows a simulation study, which investigates the differences between an AC and DC grid representation of the Smart Tinylab. Research question 4 is investigated.
- Chapter 6 details the design and implementation of the DC microgrid in the Smart Tinylab.
- Chapter 7 concludes the study, as well as gives recommendation for future work and lessons learned.

2 DC Microgrids

This chapter investigates DC microgrids in depth. First, DC grid components are examined, followed by an investigation into possible DC grid control methods. Subsequently, DC grid systems designs are examined. Next, the challenges of the integration of DC grids into our current infrastructure are presented, whereby both technical and more safety related issues are analysed. Finally, household DC grid loads are investigated.

Before proceeding, it is useful to have a formal definition of a DC grid and relevant terminology. A DC grid is an electrical power system that uses Direct Current (DC) electrical energy to power loads and devices. Furthermore, a DC microgrid is a localized DC power distribution network. It consists of a system with more than two terminals and with at least one meshed DC line [27]**.** A terminal is where power is exchanged between the DC grid and a AC system or another DC system. To facilitate the connection with another DC system, a DC/DC conversion is required (for stepping up voltage a boost converter and for stepping down voltage a buck converter). New terminals can be added to the grid to make it bigger. There can exist multiple nominal DC voltage levels and there can be multiple power flow paths between two grid terminals, which are useful to create fault tolerance. Furthermore, fault lines must be isolated using a protection technology, to ensure continuity of service in the event of a single line failure.

A DC grid typically consists of several key components, including power generation sources, power converters, energy storage systems, power distribution system, control and monitoring systems and loads [28]**.** Each of these components plays a critical role in the operation and performance of a DC grid. In this section, there will only be an overview of the DC producers, consumers, power converters and control schemes as these can differ specifically in respect to AC grids.

2.1 Components

Both this section and Section 2.2 answer the research question 'What are the components and techniques necessary in order to have an LV DC grid system, which can be connected to an existing AC LV/MV grid?'

2.1.1 DC producers

Direct current is generated by the conversion of other forms of energy, such as chemical, mechanical or solar radiation, into electrical energy that flows in only one direction. It is important to note that ESS, such as batteries and supercapacitors, can function as both sources and consumers of direct current (DC) power. Their role depends on whether they are being charged or discharged. A short introduction to DC technology based producers is given in the following sections.

2.1.1.1 Batteries

Batteries, such as lithium ion and lead-acid, are the one of the most common sources of DC, and they are used to power a wide range of devices and equipment, from electronic devices to electric vehicles. Batteries are able to convert chemical energy into electricity through the chemical cells that they are composed of. These cells have two electrodes made of metallic compounds which are immersed in an electrolyte solution which is a liquid that conducts ions between the electrodes [29]. A battery is charged because a chemical reaction takes place inside of it that charges particles and it incites them to move from the negative electrode to the positive one through the electrolyte, creating a voltage between the electrodes (anode and cathode) [30]. When a battery is connected to a circuit, for instance a light bulb as it is depicted in Figure 3, the chemical reaction is reversed, and the charged particles from the negative electrode move to the positive one creating a current and powering the device. Since the flow of the charged particles is unidirectional, the current that batteries produce is DC.

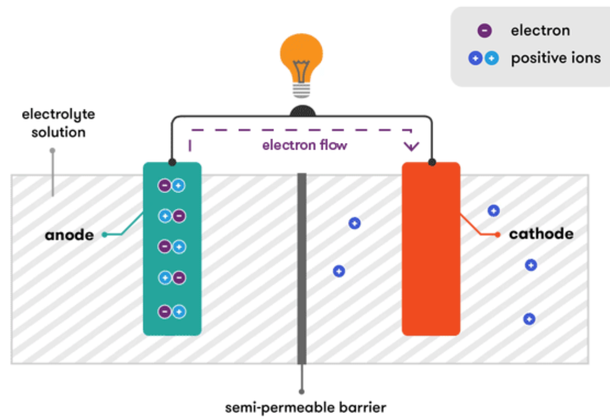

Figure 3. Representation of a battery [29]

Batteries are a great ally of renewable energy sources. They are able to store the excess energy of the fluctuation renewable power sources, such as wind and specially solar panels, and supply it whenever there is a demand for it. This helps with the grid flexibility. As a result, it is not surprising to observe a correlation between the growth in wind and solar capacity and the installed storage capacity that can be seen in Figure 4 [31].

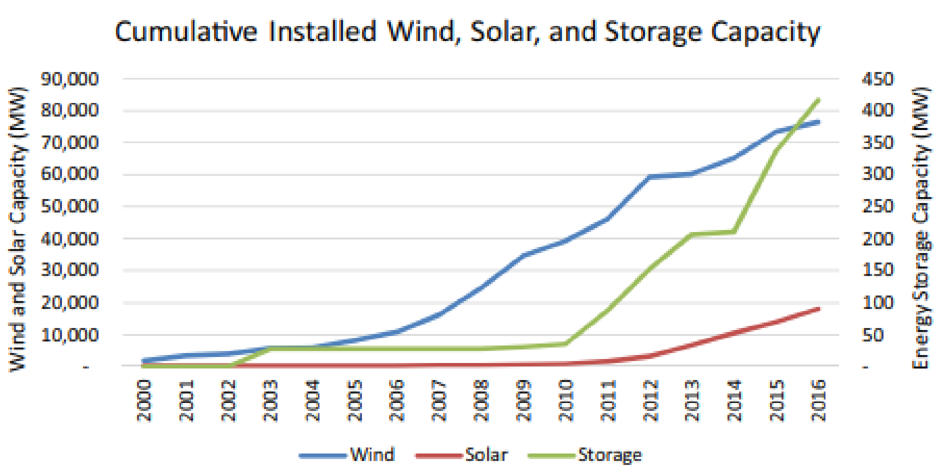

Figure 4. Acceleration of wind, solar and storage installations in the U.S [31]

In a household setting, there is typically a significant power imbalance during working hours, as occupants often leave their homes for work when solar production is at its peak. When they return home, usually in the evening, it is the time when they begin cooking, taking hot showers, and engaging in activities that require more energy. By this time, the hours of peak PV (photovoltaic) production have already passed. To mitigate or even eliminate this issue, batteries can be introduced in the power balance equation to storage the energy surplus and use it when it is most needed. If several households with these characteristics join together, they can create a microgrid. In this case, they can practice Peer-To-Peer (P2P) energy exchange, where the supply and the demand of energy can be balanced within the community. Figure 5 shows the effect that including batteries on a community has on the self-sufficiency of itself. [32] Conducted a study using real-world data from a case-study neighborhood consisting of 250 residential buildings with a mix of prosumers (inhabitants that can supply their own energy demand) and consumers.

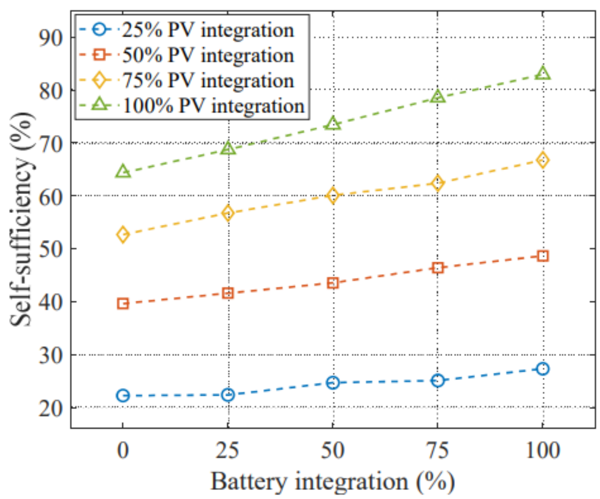

Figure 5. Level of self-sufficiency in a community with different ratios of PV and battery integration [32]

As one might expect, the self-sufficiency of the neighborhood improves as the penetration of PV systems and battery capacity increases. However, measuring self-sufficiency is challenging and has many assumptions as it relies on human behavior and it is also influenced by atmospheric fluctuations

2.1.1.2 Supercapacitors

Unlike batteries, supercapacitors rely on the physical separation of positive and negative charges to store energy to later produce it [33], as it can be seen in Figure 6. The basic structure of a supercapacitor consists of two electrodes, separated by an electrolyte solution. When a voltage is applied to the electrodes, charged ions in the electrolyte solution are attracted to their respective electrodes, creating an electrical double layer that stores energy in the form of an electric field. Supercapacitors have several advantages over traditional batteries depending on the application. They can charge and discharge very quickly, making them ideal for applications that require high power output over short periods of time. They also have a very long cycle life, meaning they can be charged and discharged many times without degrading. Additionally, they have a high power density, meaning they can release a lot of energy quickly, and a high charge/discharge efficiency, meaning they can convert a high percentage of the stored energy into usable electrical power [34].

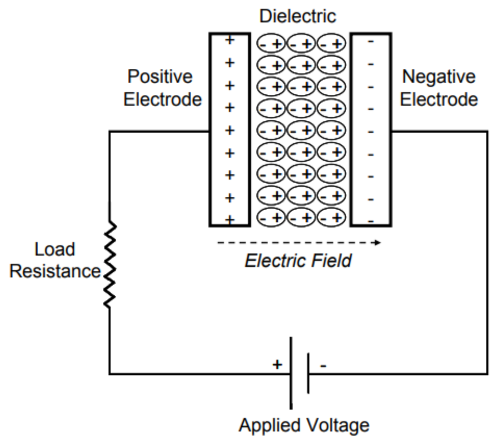

Figure 6. Schematic of a conventional supercapacitor

Within a microgrid setting, batteries and supercapacitors play distinct roles in addressing power fluctuations. Batteries are well-suited for absorbing low-frequency power fluctuations, while supercapacitors handle high-frequency power fluctuations. Batteries deliver the long-term power demand while supercapacitors respond to the short-term power variations during transient process. In this way, both energy storage devices can complement each other in a DC microgrid [35]. Figure 7 represents the improved DC link voltage, or DC bus voltage, in a microgrid composed by a fuel cell, PV, a battery and supercapacitor. The fluctuation of the voltage link is due to a reduced solar irradiation, from 1000 W/m2 to 600 E/m2, that is translated in a power decrease of the renewable source. The system stability is reduced swiftly with the incorporation of the supercapacitor as it can be seen in the green curve unlike when there is only a battery, red curve.

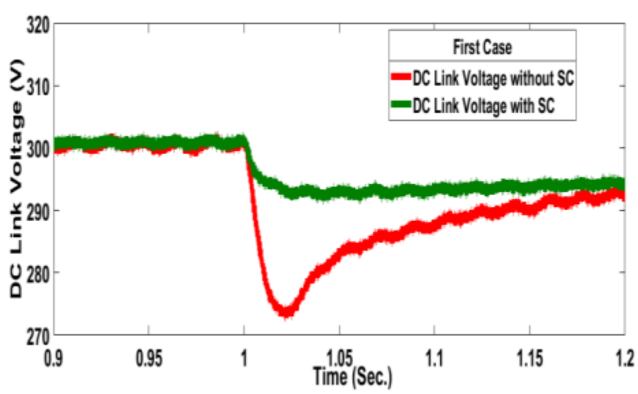

Figure 7. Comparison between voltage drop of DC link voltage before and after the incorporation of a supercapacitor [35]

2.1.1.3 Photovoltaic cells

Photovoltaic (PV) cells, or solar cells, are devices that convert sunlight into DC electrical energy. These cells are composed of two semiconductors, a n-type and an p-type joined together in a p-n junction [36]. When light strikes the cells of a solar panel, some of the energy that is contained in the light, is transferred to the n-type semiconductor, charging it and causing an electric field [37]. The electric field produces an unidirectional current which can power loads that are connected to it.

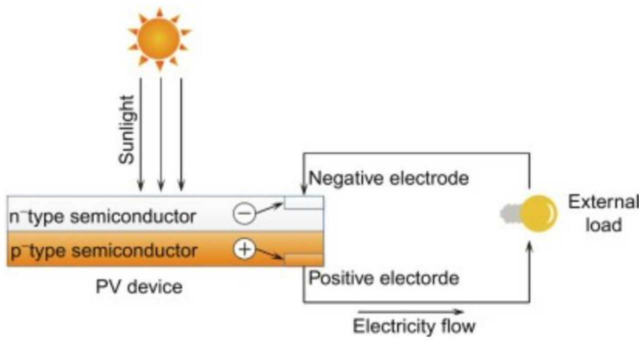

Figure 8. Schematic of the photovoltaic effect [36]

Amongst the DC producers, the current popularity of photovoltaic cells is undeniable. As concerns about climate change and carbon emissions intensify, photovoltaic cells have emerged as an appealing solution for generating electricity without contributing to greenhouse gas emissions or air pollution [38].Advancements in PV technology have played a role in their increasing popularity. Over time, significant reductions in manufacturing costs, improved cell designs, and technological innovations have made solar energy more affordable and accessible to a wider range of consumers. The continuous refinement of materials and manufacturing processes has led to higher conversion efficiencies, enabling solar panels to capture more energy from sunlight. This can be depicted in Figure 9 [39]. These improvements have not only made photovoltaic cells more efficient but also economically viable, attracting homeowners, businesses, and utilities to invest in solar installations.

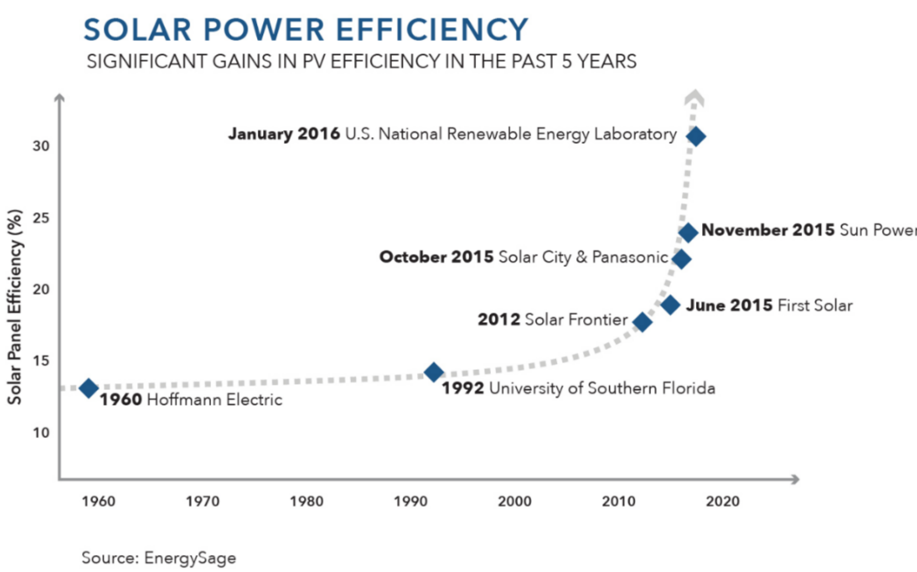

Figure 9. Evolution of solar panel efficiency over the years [39].

The desire for energy independence has also fueled the popularity of PV cells. By installing solar panels, individuals and communities can generate their own electricity on-site, reducing their dependence on centralized power grids.

On top of that, government incentives and policies make solar energy systems more financially attractive for homeowners and business. The European Union has committed to increase its 2030 target for renewable share to 45% [12]. To do so, the EU has presented a Solar Energy Strategy that, amongst other things, states the following:

- All new public and commercial buildings, with useful area larger than 250 m^2, will have a compulsory solar energy system in the rooftop by 2026. By 2027, this will also apply for all existing public and commercial buildings.
- The EU and Member states will eliminate administrative obstacles for cost-effective extensions of already installed solar systems.
- The EU and Member states will develop strong support structures for rooftop installations, incorporating energy storage and heat pumps as well, with predictable return-on-investment periods that are less than a decade.

On this context, the alignment between the exponential popularity of DC-based technologies, like PV, batteries and electrical vehicles, present the potential of DC grids in a household level, as it is an opportunity to optimize energy consumption and make the most of the renewable energy resources.

2.1.1.4 Fuel Cells

Fuel cells are devices that use a chemical reaction to produce DC power from a fuel. They are often used in applications where a reliable source of electrical energy is required, such as in backup power systems and on spacecraft. The most commonly used fuel is hydrogen, but methanol and methane can also be supplied. Hydrogen is fed into the anode (negative electrode) while an oxidant, often oxygen, is fed to the cathode (positive electrode). An electrochemical reaction takes place in the electrodes producing an electric current that goes through the electrolyte [40] [41]. Once again, this current undirectedly flows causing it to be DC. Although there are many similarities between fuel cells and batteries, fuel cells are an energy conversion devise while batteries are an energy storage system. Batteries will stop producing energy whenever the chemical reactants are consumed while fuel cells will stop producing energy for as long as the fuel is supplied.

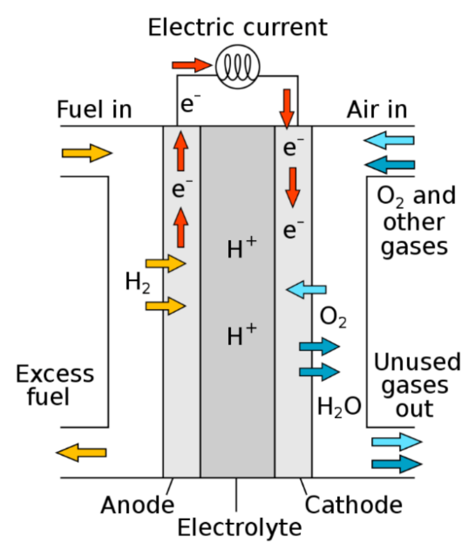

Figure 10. Scheme of a fuel cell where the fuel is hydrogen [40]

As a byproduct of electricity, water and heat is produced [42], making the technology appealing for a household use, as it can produce electricity and heat at the same time. This phenomenon is called Combined Heat and Power (CHP). By consuming heat and electricity, the overall energy efficiency can be increased up to 90% [43]. If the waste heat is recovered to produce useful cooling, then it is a trigeneration system. Figure 11 shows the use of CHP with a fuel cell. The excess electricity can be exported to the grid or stored in a battery and thermal energy can be stored in a tank for future use. The primary challenge lies in the fuel source for fuel cells. Currently, the existing gas distribution network is designed for transporting natural gas which in this case would be the fuel of the fuel cell. However, if we aim to transition to a more sustainable and decarbonized energy system, it becomes necessary to shift from natural gas to green hydrogen in the gas transmission lines. However, to achieve this transition successfully, we need to increase the production of hydrogen and ensure it is generated through greener and more sustainable methods.

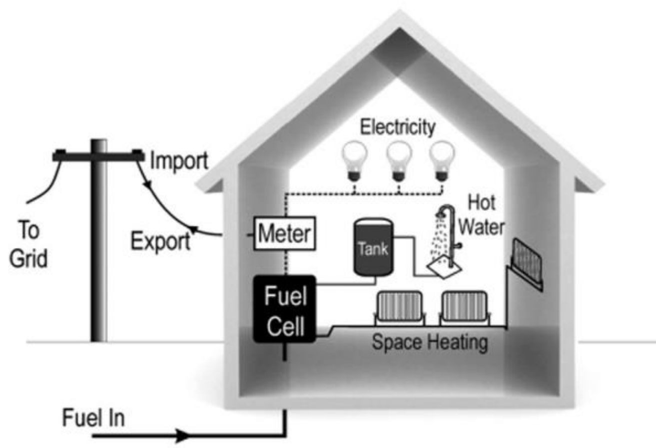

Figure 11. Fuel cell CHP in a household [41]

2.1.1.5 DC Generators

Generators are devices that convert mechanical energy into electrical energy. The energy conversion is based on the principle of the induced electromotive force. Whenever a flux is cut by a conductor, a electromotive force is induced causing a flow if the conductor circuit is closed [44].

Generators can produce AC or DC depending on their application. It is common for small-scale wind turbines with power capacities below 10 kW to generate direct current (DC) electricity through a DC generator. This is often because they are connected to off-grid installations, where battery charging systems, DC/AC inverters, and/or direct current pumping systems are present to regulate the load [45]. When it comes to higher power capacities, AC generators are used for wind turbines. In situations where electricity needs to be transmitted over long distances, such as in offshore wind farms, a two-step conversion process is often employed. First, at the wind farm, there is a conversion from alternating current (AC) to direct current (DC). Then, at the distribution center or receiving end, the DC power is converted back to AC. This is due to the fact that AC has much more capacitive losses than DC power, especially if the conductors are close to the ground, making DC inherently more efficient to transmit electricity in offshore wind farms [46], [47].

DC generators can be implemented in a residential setting, especially in rural areas. [48] Proposes a DC system composed by PV, a wind turbine and a hydropower. The mechanical movement of the wind turbine and the water when it passes through a turbine, can be used to generate electricity to power certain loads.

2.2 Power conversion

Power conversion is essential in electricity networks. Hereby, power conversion is defined as the increase or decrease of voltage and current, in order to allow power flow between electricity grid sections with incompatible voltages. The application of this on the component level is often referred to as power electronics [49]. Power electronics can further be divided into four types of converters, which are (I) AC/DC conversion, (II) DC/AC conversion, (III) DC/DC conversion and (IV) AC/AC conversion. Note, the electricity type on the left side of the / denotes the primary side power input type, and electricity type on the right side of the / denotes the secondary side output type.

As this report focuses primarily on DC grids and the interconnections they have with AC grids, AC/AC conversion, which is achieved using power transformers is not considered further. The remaining types of conversion are explained below. Each conversion type is described technically, and where possible links to DC grids are made. This section is intended to be a summary for non-electrical engineers to understand the basics of how power electronics work, as at least a basic understanding is needed to understand the challenges and advantages of DC grids.

2.2.1 AC/DC and DC/AC Conversion

Conversion between AC and DC is achieved through two separate components, a rectifier (AC/DC) and an inverter (DC/AC). Furthermore, bidirectional conversion between AC and DC is also possible. All of these possibilities are discussed in the following sub-sections. Unless otherwise stated, all information from this section is taken from[50]

2.2.1.1 Rectifier

A rectifier is used to convert AC power to DC power, or otherwise stated to power a DC load with an AC source. There are two main types of rectifiers, half wave rectifiers and full wave rectifiers.

Figure 12 shows a simplified version of a half wave rectifier with a resistive load. Hereby, a diode is included which allows positive current flow from the positive terminal to the negative terminal. The half wave rectifier is so called as it only passes the positive part of the input AC voltage. Therefore, it has a lower efficiency than its full wave counterpart [51]. Furthermore, the half wave rectifier is mostly suited for low-power applications , as the non-zero average current can cause problems for transformers. It is therefore not used often in electricity grids.

Full wave rectifiers are more widely used. Hereby, the efficiency of it is higher than that of the half wave rectifier, the average current source is zero, and the DC output of the rectifier has less ripple. Ripple here is defined as the fluctuation that occurs in the DC signal as a result of the AC signal input, and should be reduced in order to avoid damage to sensitive equipment [52]. Rectifiers can be single phase bridge rectifiers (see

Figure 13) or center-tapped rectifiers, or three phase (see Figure 14). In order to control the outputs of the rectifiers and therefore adjust the voltage, diodes can be substituted by controlled switches. These controllable rectifiers, available in both single and three phase, are suitable for a number of applications such as motor drives and heating and lighting control (dimmers) [53]. More important to this research, they can be used in battery chargers, EV chargers and power supplies for electronic devices such as mobile phones or laptops.

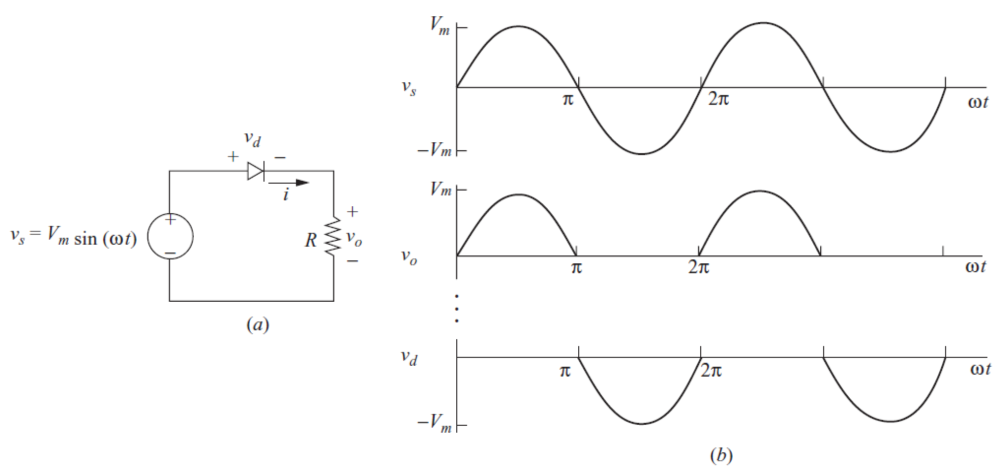

Figure 12 Half wave rectifier with a resistive load and the input and output waveforms [50]

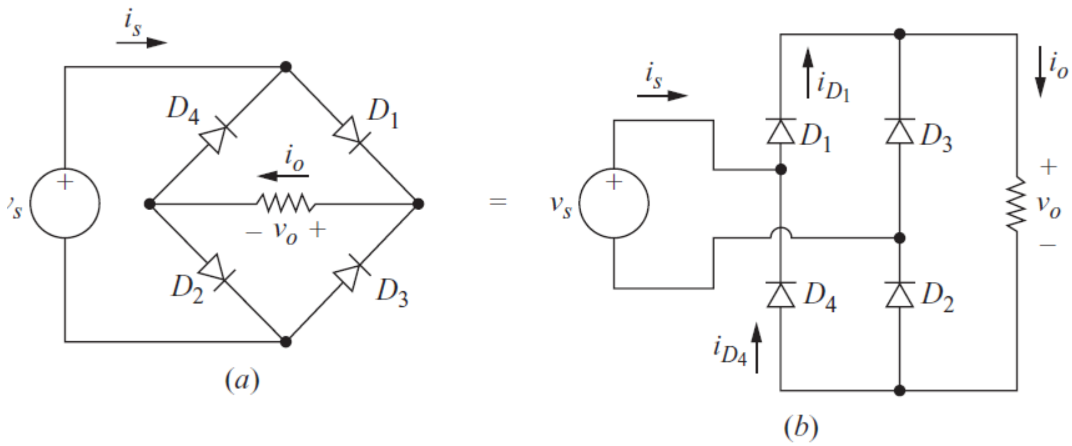

Figure 13 Single phase bridge rectifier in (a) general representation and (b) alternate representation [50]

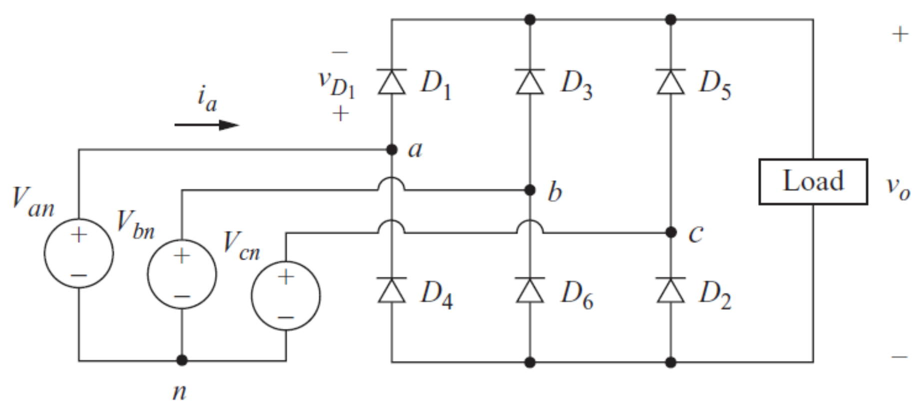

Figure 14 Three phase full bridge rectifier [50]

Finally, controlled rectifiers have been used in grids with DC transmission lines. Figure 15 shows two AC systems linked by a DC transmission grid. While there are multiple advantages to DC transmission lines a disadvantage is that converters are required on both ends of the system, which must be controlled. Additionally, filters are required to handle harmonics.

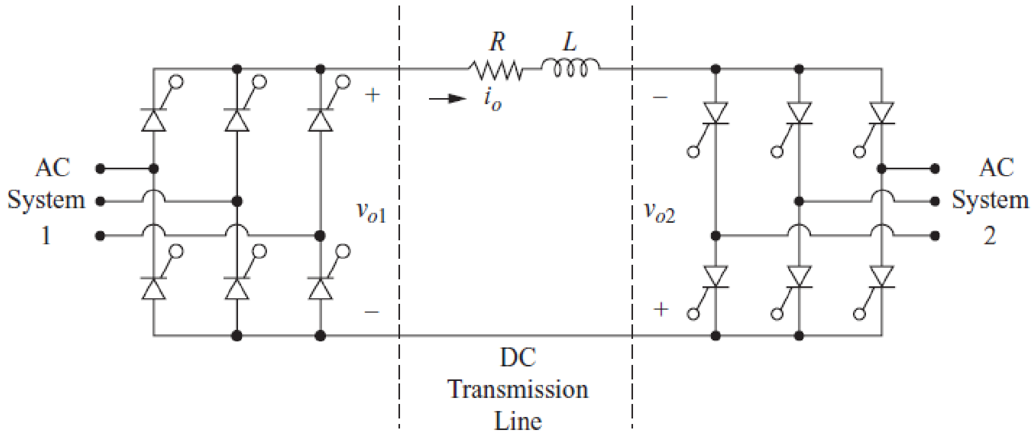

Figure 15 Example of a DC grid transmission system linking AC grids with full bridge rectifier conversion [50]

For DC grids, DC/DC conversion in the form of one or more Active Frond Ends (AFE) is preferred. An AFE is a form of controllable rectifier for three phase systems, with high efficiency and reliability while minimizing potential harmonic disturbances [54]. A simple version of an AFE for a motor supply is shown in **Error! Reference source not found.**, where the typical diodes shown in Figure 15 are replaced Insulated Gate Bipolar Transistors (IGBT) [55]. These transistors are the active component in the AFE, electronically switching the circuit to reduce the Total Harmonic Distortion (THD). For more on THD see Section 2.2.1.2. In the case of this motor drive system, power is bidirectional, which is an advantage when trying to recuperate braking energy in for example EVs.

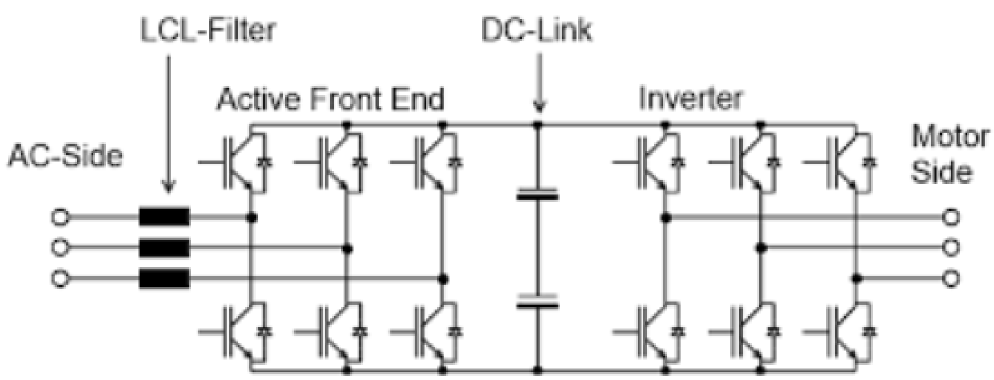

Figure 16. Simple version of an Active Front End [55]

Many topologies for three phase rectifiers exist, many of which can function as an AFE. [54] Investigates the use of AFEs specifically for EV DC charging applications, and gives a comprehensive overview which is shown in ***Error! Reference source not found.****. Important criteria for choosing a topology include the maximum power exchange desired, the maximum THD desired in the grid, if the system should have bidirectional power exchange, and the system cost which is mostly linked to the number of the components in the system. For DC grids connected to AC grids, bidirectional power exchanges is necessary, specifically for situations when the DC grid can be used to balance an AC grid's power.*

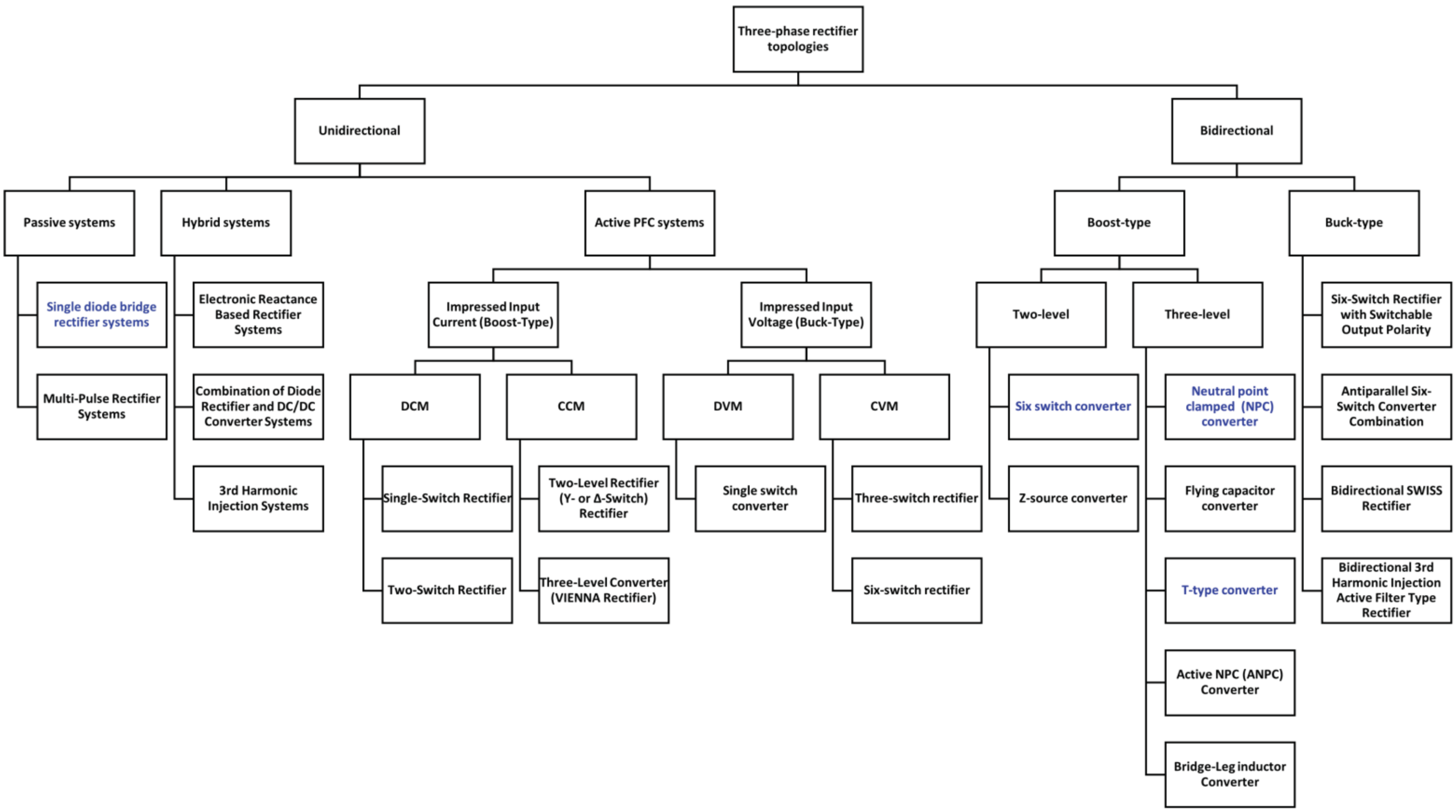

Figure 12

Figure 17. Three Phase Rectifier Topologies [54]

2.2.1.2 Inverter

For DC to AC conversion, inverters are used. Hereby an inverter converts power from an AC load to a DC source. The converters bookending the transmission lines in shown in Figure 15 did not require an inverter as AC sources existed already. However, an inverter is generally used in situations where only a DC source is available, which must be used to create an AC voltage.

As with the rectifier, both half wave and full wave variants exist. The half wave inverter only creates a positive AC wave, where a full wave inverter creates both a positive and negative AC wave. **Error! Reference source not found.** shows the circuit diagram of a full bridge inverter. Here, four switches are activated in a desired sequence in order to create the AC waveform. The uncontrolled inverter output has a non-sinusoidal square wave form (see **Error! Reference source not found.**). However, although this square waveform is applicable to some electrical appliances, others require a more sinusoidal form they are less efficient than sinusoidal waveform inverters [56]. In order to improve power quality (in this case lower harmonics and increase amplitude), the inverter can be switched in a more controlled way. One way of doing this is with Pulse Width Modulation (PWM).

PWM is used to lower Total Harmonic Distortion (THD), which is the non-sinusoidal property of a waveform. THD can be used to describe the quality of the inverter output. The IEC 61000-2-2 standards exist for THD, specifically for electronics which must not be exceeded [57]. Therefore, inverters must create AC voltage outputs which stays within THD standard limits, usually with PWM. **Error! Reference source not found.** shows the switching input and reference signal of a PWM controlled inverter. Here it is important to note that when the carrier signal is higher than the reference signal, the switch is open and no current is conducted. Conversely, when the carrier signal is lower than the reference signal, the switch is open and current flows to the output. This rapid switching creates an output voltage which approximates a sinusoidal signal.

Inverters are often already used in low and medium voltage AC grids to connect loads that are DC based, such as solar PV and batteries. In DC grids, inverters will no longer be required for these loads, and the emphasis of power electronics within a given microgrid will shift more towards DC/DC conversion. However, if certain loads can only be powered by AC power, such as AC motor based loads (washing machines), inverters will remain necessary as DC grids are rolled out.

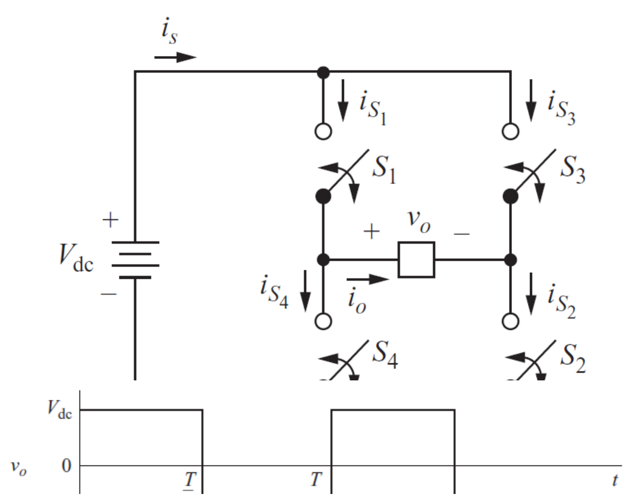

Figure 19. Block wave output of full bridge rectifier [50]

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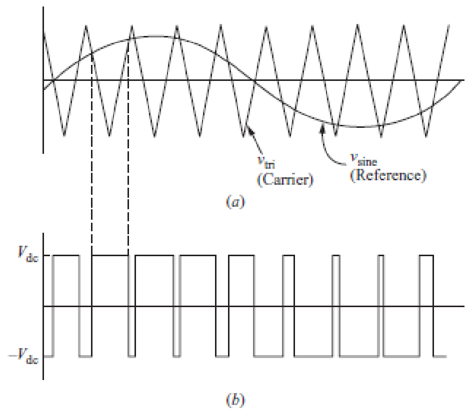

Figure 20. Waveforms of PWM with (a) triangular reference signal and (b) switching input [50]

2.2.2 DC/DC Conversion

Unless otherwise stated, all information from this section is taken from [50]. In DC grids, more DC/DC conversion is required. DC/DC conversion is achieved through the use of many types of converters. DC/DC conversion is needed to connected a DC load to a DC source with incompatible voltage levels. Examples are low voltage appliances such as laptops, PV and battery storage devices. Figure 21 shows an overview of basic DC/DC converter classifications for PV applications from [58], which has a comprehensive overview of these converters. Figure 21 makes a distinction between isolated and non-isolated converters. Hereby non-isolated converters share a common ground and therefore current can flow directly between both sides, and isolated converters which do not share a common ground [59]. Isolated converters are more flexible and are safer, however non-isolated converters are more expensive and generally smaller and lighter. Non-isolated converters tend to be used for low voltage electronics [60].

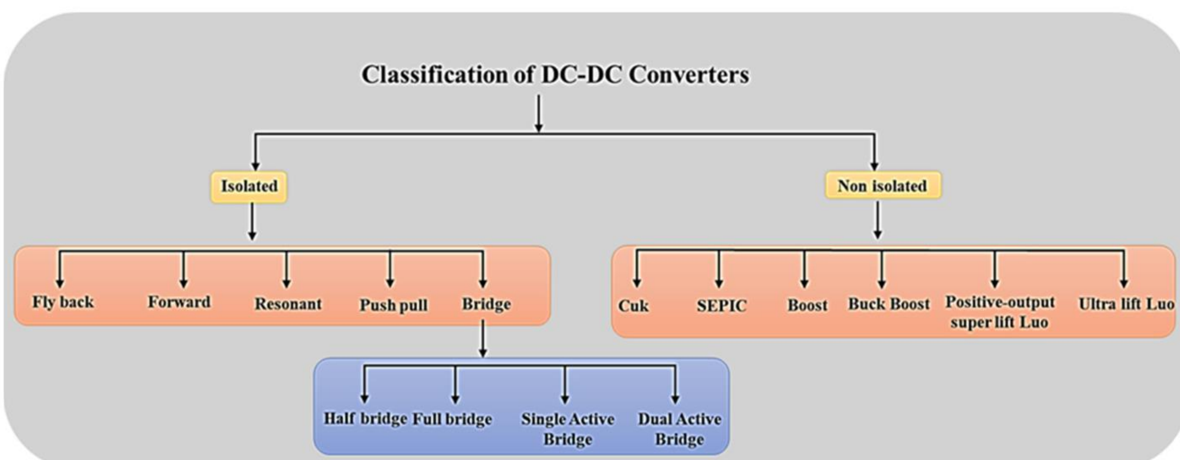

Figure 21. An overview of DC/DC converter types, specifically for PV connections [58]

The main basic converter types are buck (voltage step-down) converters, boost (voltage step-up) converters and flyback converters. Note that in Figure 21 does not show a buck converter, as a step down only converter is not useful in a PV connected DC grid system, as the PV voltage is never higher. It does however show a buck boost converter, which is a combination of the two and is capable of stepping up and down. The following sections describe the buck boost converter and the Bridge converter, as combinations of these two converters are widely used in DC grid designs [61].

2.2.2.1 Buck and Boost Converters

Buck and boost converters are similar to inverters in that they are based on the principle of switching. Buck converters (see

Figure 22) switch the circuit on and off in such a way as to create a near constant output DC voltage. The switch and diode alone are not enough to achieve this, also a filter is needed, in this case an LC low pass filter. This ensures that the output can be considered constant, and therefore DC. The capacitor in parallel to the output keeps the output close to a steady value. In practice however, this is difficult to achieve, and ripple is often present in the output signal. Figure 23 shows the capacitor current and the output voltage ripple. The capacitor current can be seen to be charging and discharging dependent on the switch position at any given moment. This charging also causes the ripple at the output voltage. In theory, an infinitely large capacitor would ensure a constant output voltage, but in practice this is not achievable. Electronics have a tolerance to handle a small amount of ripple, but too much can cause circuits to not operate correctly or break. Additionally, ripple lowers the efficiency of a system [62].

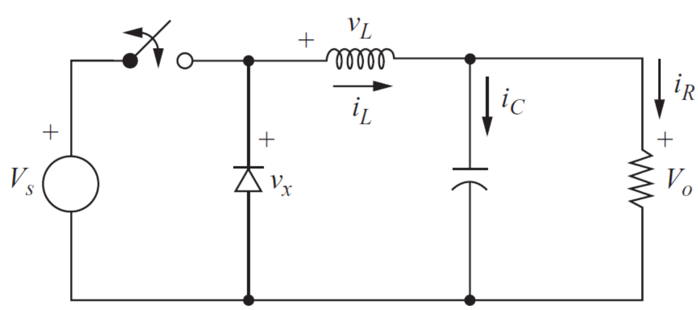

Figure 22 Buck Converter circuit diagram [50].

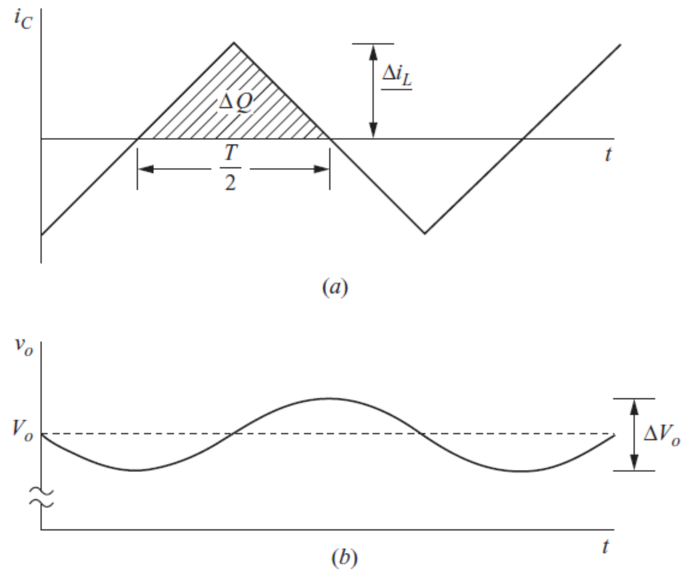

Figure 23 Buck Converter Output Waveforms (a) current (b) output ripple voltage [50]

The boost converter (see Figure 24) works with a similar principle to the buck converter. However, now the output voltage is higher than the input voltage. In comparison to the buck converter in Figure 22, the positions of the diode, switch and the inductor have been altered. The capacitor remains in parallel to the output voltage, and its use it identical to that of the buck converter, in order to reduce ripple.

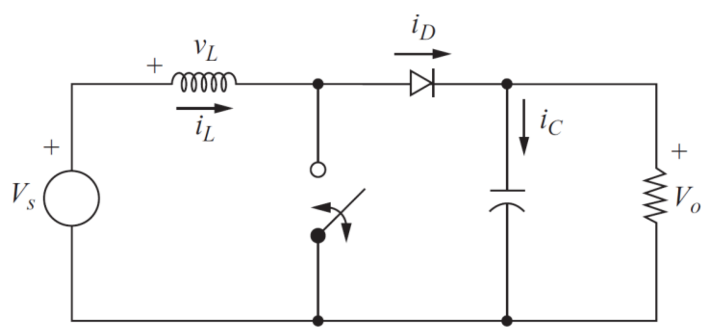

Figure 24 Boost Converter circuit diagram [50]

Finally, the buck-boost converter (see Figure 25) can either step up or step down the voltage. Again, the switch, diode and inductor have switched positions, and the capacitor is used to reduce ripple. This solution can be applied in situations where both a step up and step down are needed, with a minimum of extra components. However, the main drawback is a reduced gain due to a lower efficiency [63]. Therefore it may be suitable in some situation to have a buck and boost converter separately.

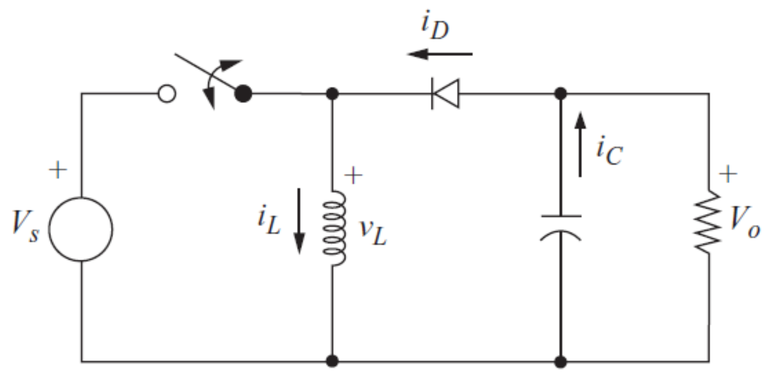

Figure 25 Buck-Boost Converter circuit diagram [50]

2.2.2.2 Flyback and Bridge Converters

Other than non-isolated converters such as buck and boost converters, isolated converters can also be used in DC/DC conversion. Isolated converters physically separate the input and output parts of the system, dividing the system into two or more circuits. The circuits are joined together usually by a transformer, typically called an isolation transformer. The circuits can also be joined together by coupled inductors [64]. Isolated converters tend to be used in situations where safety is an issue, for example for systems where humans come into contact with the system and could be endangered. Furthermore, they are useful for breaking ground loops, which can combat noise transfer from one circuit to another [64]. While isolated converters have advantages which can be useful in for example DC household systems, these converters tend to be more expensive, larger in size due to the transformer, and less efficient than the non-isolated counterparts.

The most basic type of isolated converter is the flyback converter (see Figure 26). This converter functions similar to a buck-boost converter, both stepping up and stepping down voltage as required. It also includes all of the same components, but introduced a transformer in parallel to the output of the circuit, before the diode. In addition, as with the non-isolated converters, the capacitance in parallel to the output it used to reduce the ripple of the output voltage.

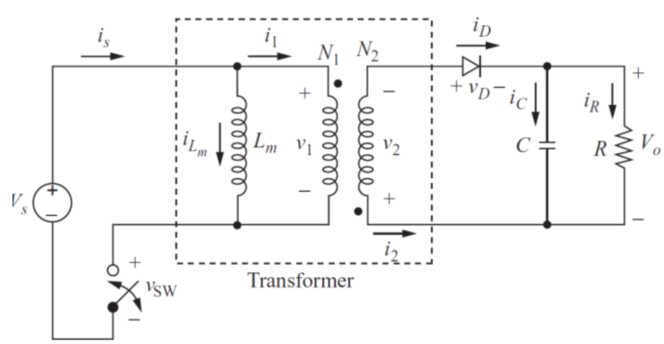

Figure 26 Flyback converter circuit diagram [50]

Another isolated converter with a higher level of complexity is the full bridge converter. This converter has four switches, similar to the full bridge inverter shown in **Error! Reference source not found.**. Although the cost of the system is higher due to the number of extra switches, as with the full bridge inverter the efficiency is also higher. Additionally, it is of note that the secondary side of the transformer has two separate winding groups, one for the positive and one for the negative voltage input.

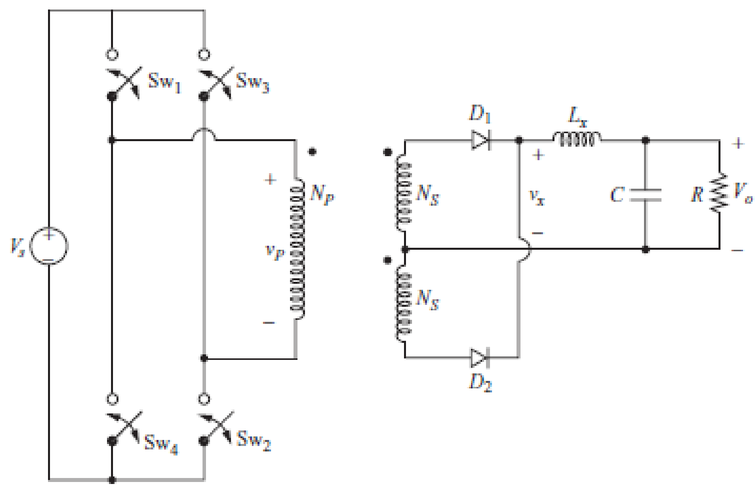

Figure 27 Full Bridge Converter Circuit Diagram [50]

According to [61], some of the most important converters for DC grids are:

1. Single phase non isolated bidirectional converters. Primarily, the cascaded buck-boost (CBB) is suitable here, with a higher discharge current and high efficiency it is more suitable for higher power applications.
2. The Dual Active Bridge (DAB) converter. As late as 2019, this was the most widely used DC/DC converter in DC grids [65]. Whether that remains the case is yet to be seen. Figure 28 shows a DAB example, for a battery connected to a DC but. Here an isolating transformer separates both circuits, and transistors are used to switch the circuit efficiently, according to a given control strategy (i.e., to ensure both sides input/output at the desired voltages).
3. Bidirectional three-port DC/DC converters. This type of converter is also often used for battery charging. This type of converter has a slightly lower cost than other Triple Active Bridge (TAB) converters, with a simpler control scheme.

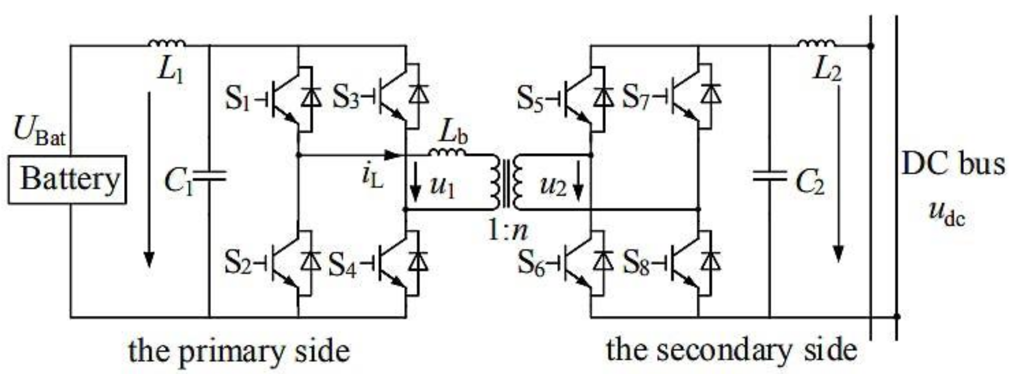

Figure 28 Dual Active Bridge Converter [61]

2.2.3 Converter Comparison

Power conversion with power electronics is ideally has no power loss, the power between the primary and secondary side of the converter is equal. However, in non-ideal (practical) situations, this is not the case. As power is converted from one form to the other, energy losses occur in the form of heat. These losses vary from the type of converter and the type of technology, as it is shown in Figure 29 [66].

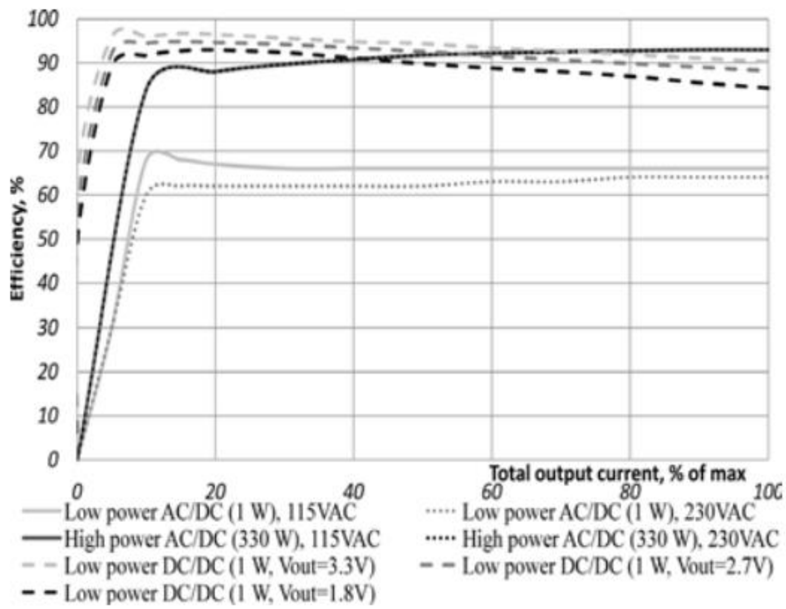

Figure 29. Power conversions efficiency curves [66].

There is a clear correlation between high power and higher conversion efficiency. This is due to the fact that power loss is proportional to the square of the current, and at lower voltages, higher currents are required to deliver the same amount of power, leading to higher power losses. Additionally, regardless of the outputted voltage, the power conversion from DC to DC is more efficiency in low power situations than AC to DC, making DC/DC power conversion more convenient of a household level [66]. On top of that, if energy generation and consumption both happen in the DC domain, and no outside energy is needed from a connected AC grid, redundant losses from the AC/DC conversion will disappear.

Multiple studies such as [67], [68] and [69] have been conducted to estimate the energy savings achieved by avoiding AC-DC power conversion losses. According to [67], avoidable conversion losses for residential appliances amount to approximately 14%. Table 1 below provides a comprehensive overview of the energy savings of several home appliances resulting from the avoidance of AC-DC power conversion losses.

Table 1. Energy savings from avoided AC-DC power conversion losses [67]

Appliance	Energy savings from avoided AC-DC power conversion losses
Refrigerators	13%
Freezers	13%
Dishwasher	12%
Electric water heaters	12%
Room air conditioners	11%
Electric cooking equipment	12%
Lighting-Fluorescent	18%
Home audio	21%
Computers	20%
Rechargeable electronics	20%
TV's	17%

2.3 DC Consumers

The consumers of a DC grid are the load points that use the DC electrical energy. This can include anything from electronic devices, electric vehicles, to large industrial machines and equipment. As previously stated, any device that works directly with a battery with no conversions is DC-based. Moreover, any device that works with a circuit board uses direct current, as the nature of those chips only tolerate unidirectional flow of electrons to function and store data [70]. Table 2 gathers information about the devices of a household that can be directly connected to a DC or AC grid. As previously stated, AC/AC and DC/DC converters can be used to adjust the input voltage level to ensure it is at the correct voltage for a specific application.

Table 2. Nature of consumers in a household depending on energy conversion

Energy conversion	Appliances	AC supply		DC supply		Source
		AC/AC converter	AC/DC converter	DC/AC converter	DC/DC converter	
Electric energy to Heat	Boiler, coffee maker, light bulb, electric cooker	Yes	Yes	Yes	Yes	[71]
Electric energy to rotational or mechanical energy	Washing machine, ventilator, vacuum cleaner	Yes	No	Yes	Depends on the nature of device	[72]
Electric energy to sound and vision	TV, radio, telephone, computer,	No	Yes	No	Yes	[73]

- Electric energy to heat: These devices can be powered either by AC or DC and some might have rectifiers or other conversion components to level up the voltage that the device needs. These devices are the ones that behave as resistive loads, such as kettles and toasters. Note that a conversion from DC/AC or AC/DC in this specific technology is redundant and unnecessary but possible.
- Electric energy to rotational or mechanical energy: These household appliances vary in their suitability for DC electricity supply. While it is possible to power these appliances with DC, the compatibility depends on the type of motor used in the equipment. Collector motors found in vacuum cleaners and electric drills can easily be connected to a DC power source. However, push armature motors commonly found in refrigerators, as well as shaded-pole motors, capacitor motors, and other types of induction motors, are not suitable for direct DC connection. In such cases, these motors would need to be replaced with DC motors, or alternatively, a DC-to-AC conversion would be necessary. Therefore, the feasibility of DC supply for these kind of appliances depend on the motor type and power requirements, which may entail motor replacements or additional conversion processes [72], [73].
- Electric energy to sound and vision: Devices that have integrated electronics and/or batteries, work on DC due to the nature of batteries and mother boards.

2.4 Control of DC Microgrids

This subsection answers the research question 'What active control is possible for DC grids?'

DC microgrids have emerged as a solution to address the limitations of AC microgrids, offering additional advantages due to the unidirectional flow of the current. This technology avoids the need for frequency synchronization, reactive power control, harmonic conflicts and power quality which are related issues of AC [74].

However, it is important to acknowledge that DC microgrids also come with their own set of challenges. Firstly, the intermittent nature of renewable energy sources, such as solar and wind, which are often used in DC microgrids, can pose reliability issues. The availability of power from these sources fluctuates, leading to concerns about a stable and consistent energy supply. Due to this, DC microgrids need a coordination scheme between hardware-based control and software-based optimization planning as there are continuously varying generation power and dynamic load profiles [28].

Another challenge is maintaining a stable voltage level across the connected loads in the microgrid. It is crucial to ensure that the voltage does not deviate significantly from the desired value at the bus. Deviations in voltage can impact the performance and reliability of the connected devices and equipment. Similarly, achieving equal current sharing among the various converters within the microgrid presents another challenge. Each converter should share the current load in a balanced manner to prevent overloading or underutilization of specific converters. This equal current sharing is essential for efficient and reliable operation of the microgrid [28].

To tackle these challenges, a technique called droop control is commonly used in DC microgrids. Droop control aims to achieve equal current sharing among the converters, similar to how reactive power sharing is accomplished in AC microgrids [74]. The basic idea behind droop control is to add a virtual resistance in the line to equalize the current sharing. By incorporating droop control, the converters in the DC microgrid adjust their power outputs based on the voltage deviations. If the voltage decreases, a converter utilizing droop control will increase its power output to compensate for the droop and help restore the voltage to the desired level. This ensures that the loads receive a consistent and stable voltage.

Regarding the operating control of DC microgrids, it can be divided into two broad categories:

- Grid-connected: The microgrid exchanges energy with the main grid. This can be for various reasons such as balancing the grid, price signals or during shortages or disruptions. The microgrid is linked to the utility grid using a bidirectional voltage source converter responsible for regulating the DC link voltage. In case of any power imbalance, the grid voltage source converter primarily takes charge of restoring balance [28].
- Islanded: The microgrid does not exchange energy with the main grid. However, this doesn't necessarily mean that it is not connected to it. In this case, there needs to be a sufficient ESS capacity to meet the mismatches of production and demand. In some cases, there is not enough energy stored and the demand is higher than the production of the microgrid. In this case, load shedding controllers can be incorporated to turn the loads on or off so that the power is balanced and the bus voltage controlled [75].

The control of microgrids can be implemented using various approaches, that depend on the specific characteristics of each microgrid. A well-designed control strategy must address several key aspects, including stability, protection, power balance, transition, power transmission, synchronization, and optimization [76]. Figure 30 provides a comprehensive overview of the fundamental control strategies. The following paragraphs provide a summary of the strategies:

- Centralized

A central controller gathers information from several distributed units through communication links. In return, the central controller manages accordingly the data and performs control operations by sending back reference values to the specific components. This control scheme is useful for coordinating the integration of the charging schedule of a large number of electric vehicles, as it has been studied in [77], achieving an efficient operation. However, the main drawback of this control method is single point failure.

- Decentralized

In this method, the control relays in each individual component of the microgrid. Therefore, each generation and storage device has a local controller. One of the main objective of this controls scheme is that if a fault takes place in one of the branches, the rest of the microgrid can operate normally after disconnecting the faulty unit [76]. Nevertheless, a downside of this technique is that there is no communication between the devices and that the control is based on local measurements resulting in poor accuracy. According to [78], a decentralized control scheme is useful at the power distribution level because its communication network is more simple and it also provides a plug-and-play connection of the devices.

- Distributed

The communication is made with the neighboring units depending on the available communication link. Each component has its own local controller which communicates with the neighboring ones to exchange information such as bus voltage, the output current and so on [28]. This method combines the advantages of both centralized and decentralized systems. This method makes it possible for units to have specific objectives. For instance, [79] presents a study about how in a PV system, a ultracapacitor controls the DC bus voltage whereas a battery controls the state of charge of the ultracapacitor reducing power fluctuations in an islanded mode.

- Hierarchical

In complex control schemes, where several energy storage devices, loads, renewable energy sources and distribution systems take place, a hierarchical approach is taken. In this hierarchical scheme, there is three basic control levels [80].

- Primary control, which is responsible for locally regulating the power, voltage and current of each unit through the interface controllers and therefore achieving load sharing.
- Secondary control compensates for the deviation of the primary controller.
- Third control, which is responsible for the overall control of the microgrid and maintains the optimal operation withing other microgrids or the grid.

An alternative hierarchical approach involves dividing the system into two levels. At the lower-level control, a decentralized approach is followed due to its local benefits. On the other hand, the upper-level control can adopt either a centralized or distributed approach, thanks to the overall control benefits it offers. An example of a hierarchical approach for storage devices is shown in **Error! Reference source not found.** [81].

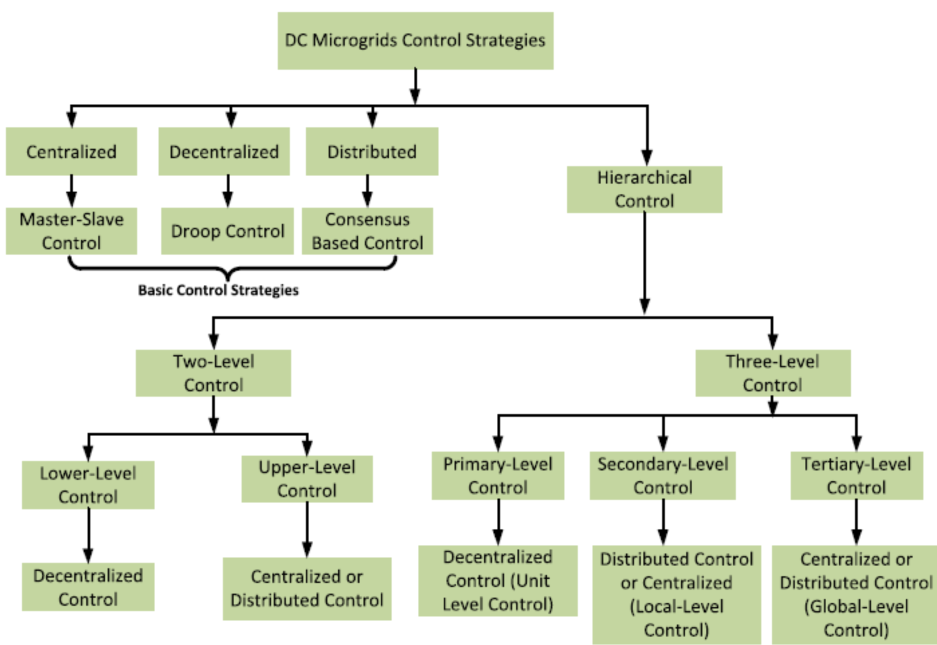

Figure 30. Control strategies of DC Microgrids [27]

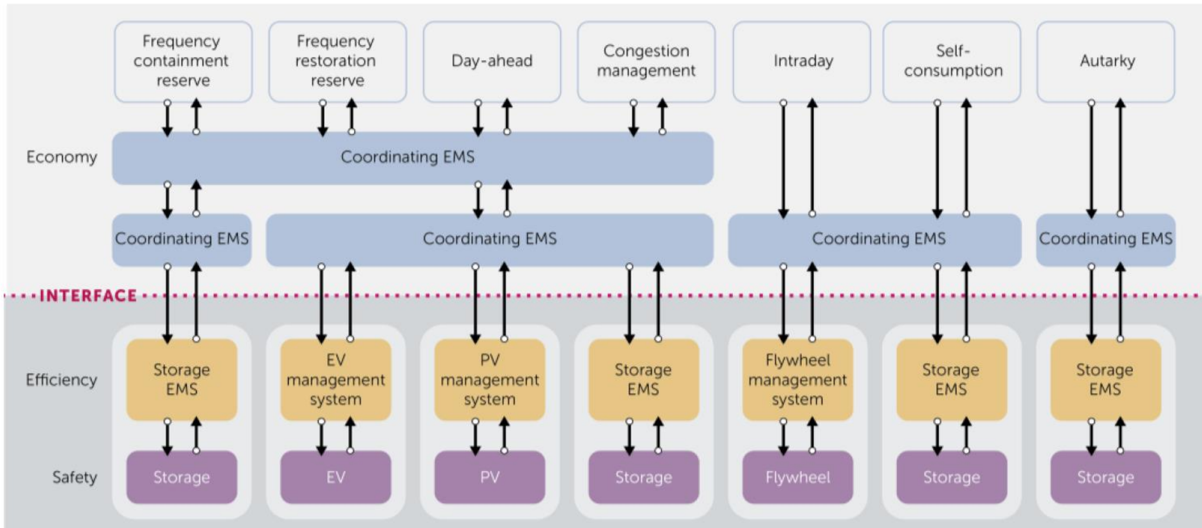

Figure 31. A hierarchical architecture for storage devices, with different management systems and goals [81]

2.4.1 Current/OS

It is useful to analyze a specific control scheme currently available on the market. The choice here is Current/OS. The Current/OS foundation [25], established by founding members Eaton and Schneider Electric, is an organization dedicated to the development of a standardized protocol for local decentralized DC microgrids. With a keen observation of the increasing grid congestion in countries like The Netherlands, the foundation recognized the need for a unified standard to address grid control challenges. Consequently, they collaborated to create an open protocol and provide clear manufacturing guidelines to their partners for producing products compatible with the Current/OS-based DC environment. Although the foundation currently comprises 10 members, it is anticipated that the number will grow as more companies become aware of the pressing grid issues at hand.

The Current OS protocol is a new approach of DC electrical distribution, some of the characteristic that are mentioned in their website are the following [82]:

-The protocol establishes energy management rules that simplify the control of microgrids by making opportunistic decisions to optimize the utilization of available electrical resources and power loads based on their priority.

-A communication model is defined by the protocol to facilitate software interaction with electrical systems. However, this introduces the possibility of communication losses and cyber-attacks, necessitating appropriate security measures.

-The protocol relies on the safety protection zones.

-It specifies the current profiles during circuit connection, pre-charge, and disconnection stages to facilitate black start capability and prevent nuisance tripping.

-Tripping criteria are outlined by the protocol to detect and respond to various faults, including short circuit faults, earth leakage faults, and serial arc faults, while ensuring bidirectional selectivity.

-Operating voltages and limits are defined by the protocol, along with guidelines for device calibration and compensation of line losses and voltage drops.

-In terms of communication, the protocol enables it by providing a data model description specifically for Modbus communication.

2.5 Challenges

This section answers the research question 'What technical challenges, including safety, do DC grids have?'

When introducing new technology, there are inevitably challenges for its integration. Specifically, as DC grids are emerging, their operation and protection face significant challenges due to a lack of standards and protocols. To address this, various organizations such as IEEE and IEC are working closely to establish the necessary standards [83].

In this case, the challenges go beyond the mere integration of DC into the AC grid system, and extend to the maturity of the technology itself. Despite the fact that DC was developed prior to AC, the greater emphasis placed on AC in residential settings has resulted in AC technology achieving a greater level of technological maturity in comparison to DC. The following sections examine specific technical, safety and market challenges which should be addressed.

2.5.1 Technical

Ensuring the protection and safety of DC microgrids is crucial for its development and adoption. Here is a list of the main protection challenges to be tackled according to [83].

- DC fault current characteristics

In a microgrid, power electronic converters are needed in order to integrate energy sources like PV, fuel cells, energy storage devices and loads. These converters, as they are small-scale distribution generators and DC sources, offer very little rotational inertia which affects the system's ability to remain stable if there is a disturbance or fault. These faults can be caused by fluctuations in load, input power variations, communication failures or delays, oscillations in MPPT amongst other faults [84].

- Dynamic fault current magnitude

In a DC microgrid, different types of faults can create varying levels of fault current. The OCR (Over Current Relay) is a protective device that detects faults and isolates the affected section of the system. However, using a fixed OCR setting for a specific fault type may lead to incorrect operation for other fault types. Additionally, DC microgrid OCRs can face dynamic fault currents due to their connection with the AC grid. The infeed from the AC grid can change the short circuit level, which makes fault protection more challenging.

Furthermore, the fault level in a DC microgrid can differ depending on whether the system is operating autonomously or connected to the grid. The converters used in DC microgrids limit the fault current for safety reasons. However, this can make it difficult to detect faults using overcurrent-based protection methods due to the low magnitude of the fault current.

To address these challenges, an adaptive OCR setting is necessary. This ensures that the protective devices can detect and respond correctly to different types of faults in a DC microgrid [85], [86].

- Bi-directional fault current

If the microgrid is connected to the AC grid, the power can flow in both directions. Distribution generators (DG) may affect the protective system as they can increase the short-circuit level if they inject an extra share of fault current changing the power/current flow direction [86]. If the microgrid is isolated, there will be no need of bi-directional protection.

- Dynamic current due to Constant Power Load

A Constant Power Load (CPL) maintains a constant power regardless of the voltage applied to it. If there is a fault, the voltage decreases rapidly while the CPLs draw massive current in order to maintain the required load. This accelerates the fault current rapidly due to Ohms Law. In [87] a method to tackle the instability that CPLs can have in to the microgrid is implemented by a local stabilizing agent.

- Grounding fault

It is a well-known fact that electric shocks can be avoided with a proper grounded system. Protection devices such as residual-current circuit breakers are used to do so. However, the way a DC microgrid is grounded can have a significant impact on the magnitude of the fault current for a ground fault [83]. According to [88], there are two main ways that DC distribution systems can be grounded, either TN systems or IT systems. This is shown in Figure 32. The IT grounding schemes in an isolated DC system can result in safer operations for the residential system and its occupants. This is due to the fact that IT grounding schemes can regulate the fault current through the use of the grounding resistances. Moreover, the occurrence of a ground fault is less likely to affect the overall operation of the system.

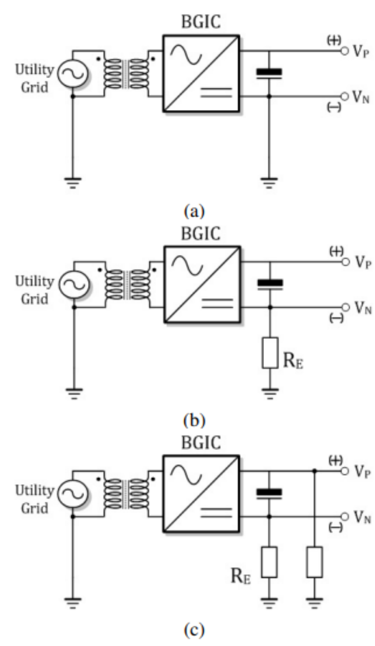

Figure 32. DC microgrids grounding schemes. (a) TN system, (b) Single pole IT system, (c) Double pole IT system.

- Fault interruption due to the lack of natural zero-crossing current

In AC power systems, the voltage and current waveform cross the zero line (or the x-axis) twice in each cycle. This zero-crossing phenomenon makes it easier to control and interrupt the current flow, especially in the event of a. However, in DC power systems, the current flow does not naturally cross zero, making it challenging to control and interrupt the current flow. This is because the lack of zero-crossing points in DC systems can result in high levels of current and voltage surges during a fault, which can lead to significant damage to the equipment and power devices. Additionally, the absence of zero-crossings makes it difficult to design and implement protective devices, such as fuses and circuit breakers, for DC power systems [83].

2.5.2 Safety

The debate over whether DC or AC electricity is safer for humans dates back to the "War of Currents" in the 19th century, a battle that aimed to prove the superiority of one technology over the other. As part of this conflict, Thomas Edison electrocuted an elephant named Topsy with AC electricity at the Luna Park Zoo in Coney Island, as a way to demonstrate how deadly AC could be [89]. When the 6.6 kV AC charge hit the elephant's body, it died instantly, which in Edison's mind, validated his point. However, in the days of Edison, the voltage levels achievable with DC power were lower compared to today's standards. Currently, we are working with DC power systems that can be lethal if not handled with proper caution.

The IEC TS 60479-1-2026 [90] provides a basic guidance on the effects of shock current on people and animals. It serves as a basic safety publication intended for technical committees in the preparation of standards. The text has divided into four groups the different effects that DC current has to the human body. This is shown in the Figure 33. DC-1 has a physical effect of a slight pricking sensation, DC-2 an involuntary muscular contraction, DC-3 a stronger involuntary muscular and the impulses of the heart may take place and the DC-4 is the most dangerous zone. Above the 500mA effects such as cardiac arrest, breathing arrest and burns may take place. According to [91], low DC current doesn’t have any immediate effect of our bodies, but the prolongated exposure can be fatal because of cumulative internal tissue that was burned.

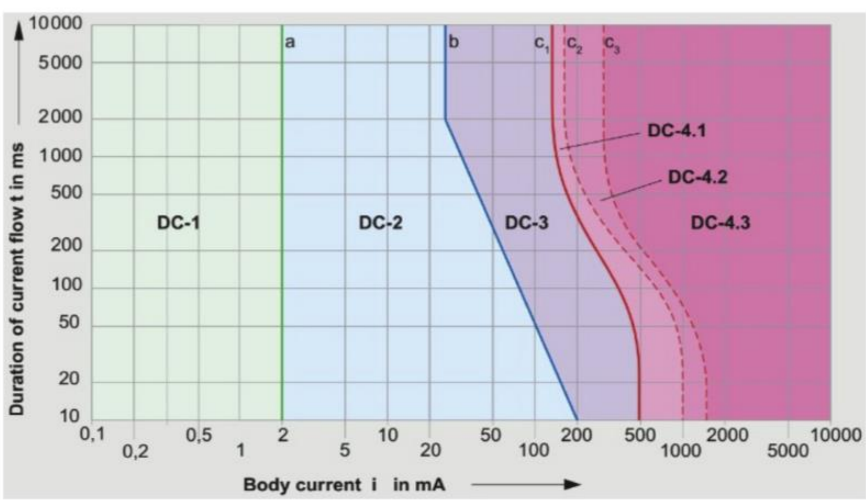

Figure 33. Effects of DC current on person depending on the current [91]

The current that passes through our body is dependent on the voltage, the body's impedance, environmental conditions that effect on our body's impedance and the power of the circuit. Therefore, the dangers of DC depend on a determinate voltage and power. An overview of the different dangers depending on these two factors are collected in Figure 34. It shows, from left, the least dangerous voltage and power zone, to right, the most lethal one.

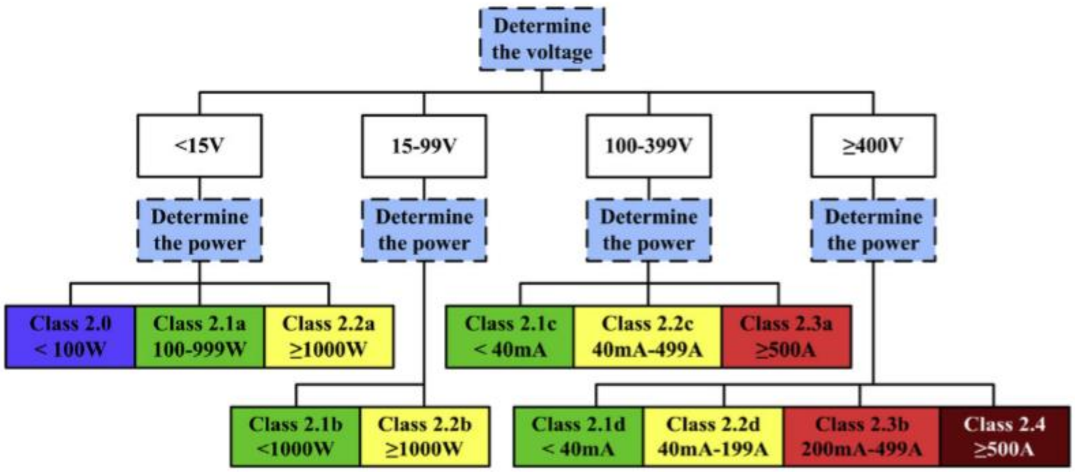

Figure 34. Classification of DC hazard classes [91]

The classes specifically mean:

- Class 2.0: No hazard.
- Classes 2.1: Little to no hazard.
- Classes 2.2: If there is a close proximity or contact, injury or even death could take place. There is often a shock or burn hazard. In this case there is a necessity of engineering controls for operation and administrative control for electrical work.
- Class 2.3: Similarly, the same applies from Class 2.2. However, in this class, arc-flash burns can also take place. These refer to the thermal and radiant energy release during an electrical fault, which can result in injuries or damage to equipment.

In summary, safety considerations are crucial when implementing DC systems. However, at a household level, as demonstrated in Table 3 (Chapter 4), devices typically operate at lower voltage levels, reducing the likelihood of significant injuries. Nevertheless, it is important to prioritize electrical controls when constructing a DC microgrid for residential use, ensuring proper installation, maintenance, and adherence to safety standards to mitigate any potential risks.

2.5.3 Market

According to [92], the development of direct current faces resistance by both demand and the supply side. The well-established AC infrastructure has long been the primary method of powering appliances, making it challenging for DC to gain traction and expand its presence. However, there are two target markets where DC has an impact today which is where there is a high presence of DC loads, such as LED lighting and in computing power [93]. DC can have a potential impact in terms of saving energy in buildings with high demand for lightning and computing power. Nonetheless, in a household level, the penetration of this technology is minimum due to the following aspects:

- Dominance of AC products and appliances due to the main AC grid.
- The current infrastructure has been built to support AC so there is a resistance to chance from the established one.
- Lack of standardization.
- Actors from the industry do not see the advantage of the change.
- The lack of interest or unfamiliarity with DC the homeowners.
- High investment risk because of the uncertainty in business model innovation.
- Uncertainty about effectiveness and value since it has not been broadly implemented.
- Low environmental awareness.
- Skills and workforce development.

3 DC Microgrid Designs

There is no single accepted DC grid design. This has to do with the maturity of the technologies often connected to DC grids as well as DC grids themselves. Therefore, an investigation into possible architectures is useful. First, bipolar and unipolar DC grids are briefly examined. Then, a more in depth analysis is conducted into household microgrids. This chapter answers the question "Which AC and DC household grid designs are considered feasible?"

3.1 Bipolar and Unipolar

DC grids generally are either bipolar or unipolar. The unipolar configuration has a two wire connection, and has a single DC voltage. In contrast, the bipolar configuration has a three wire connection with two DC voltages [94] . Bipolar configurations are more flexible and offer redundancy in the case of a single line fault. However, they can have problems with unbalanced lines (as with three phase AC grids) and the systems are more complex than their unipolar counterparts. Nevertheless, most research is currently focused on bipolar for larger networks, while unipolar is more practical for household DC grids [95]. Furthermore, often times bipolar configurations are treated as being almost the same as unipolar, just with an extra voltage line. However, both function differently from a fault tolerance point of view as shown in [96], which highlights the importance of evaluating and controlling each system according to its own unique characteristics.

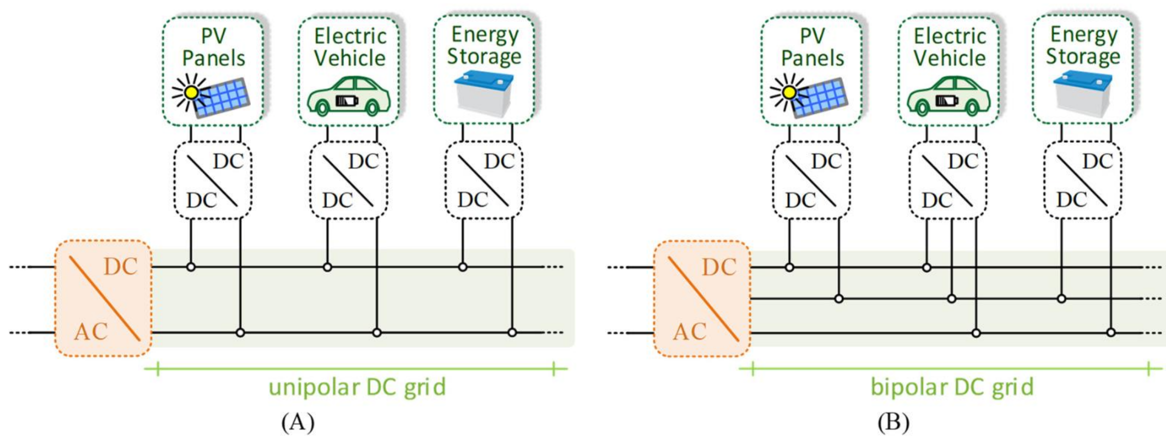

Figure 35 DC grid configurations, (a) unipolar and (b) bipolar [94]

3.2 Hybrid DC/AC

While the advantages of a DC household are apparent, several factors need to be taken into consideration: PV installed capacity, capacity of the battery, the profile of the loads, energy efficiency of the devices and even atmospheric conditions. Additionally, the exact goal has to be clear, for example reduction of losses, reduction of costs etc. Thus, it's a matter of assessing what technology is more advantageous in order to achieve a desired goal. For example, if the household already has an AC distribution system in place, it may be more cost-effective and convenient to stick with AC solutions, but if it's a newly built house, perhaps a DC grid would be a viable alternative. Another important aspect to consider is the fact that current household-level DC microgrids are connected to the AC grid. Consequently, exploring hybrid solutions can allow for the potential to combine the advantages of both AC and DC systems.

A DC/AC hybrid microgrid refers to the combination of both AC and DC networks within the microgrid infrastructure. The objective of a DC/AC hybrid microgrid is to optimize the use of available energy resources, enhance energy efficiency, and improve the overall stability and reliability of the microgrid system. By integrating both DC and AC technologies, the microgrid can effectively balance loads, manage energy storage, and optimize power flow based on the specific requirements and characteristics of the system.

The specific configuration and design of a DC/AC hybrid microgrid can vary depending on the scale, location and goals of the microgrid deployment. It often requires sophisticated control and management systems to ensure integration and efficient operation of the hybrid system. Furthermore, AC/DC hybrid grids can generally be categorized as either coupled or decoupled [94]. Coupled hybrid grids link the grids with a transformer on the AC side and DC voltage created through a rectifier. The grid configuration here can either be fully isolated or partially isolated. In contract, the decoupled grid does not incorporate a transformer and has power converters on the AC side, which again can be either fully or partially isolated. Decoupled grids are generally more expensive due to the increased cost of the power converters (stepping down in AC is generally cheaper with a transformer).

Figure 36 [11] and Figure 37 [5] both depict a possible hybrid system. Companies such as DC Systems appear to be advocating a hybrid grid structure in the Netherlands as opposed to a complete switch to DC, as there is already a working AC grid in place. However, this grid will not be sufficient to handle the introduction of more RESs as well as new loads.

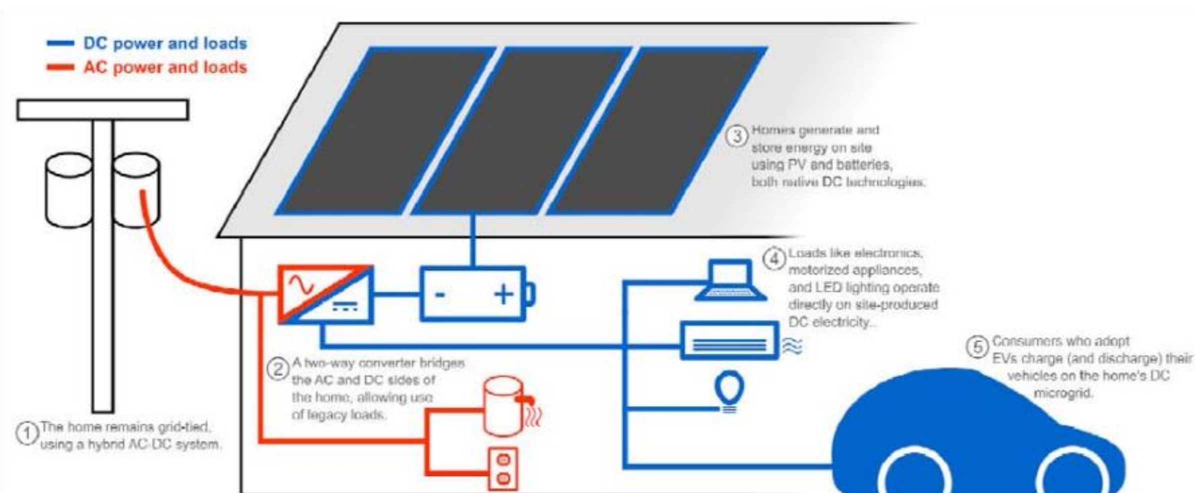

Figure 36. Hybrid DC home [11]

By incorporating a hybrid DC system in a home, the need for unnecessary power conversions can be minimized. However, to establish a connection between the home and the AC grid, a two-way inverter is still required. This inverter serves as an interface, converting the DC power generated on-site into AC power for export to the grid when there is surplus energy. Similarly, it can convert AC power from the grid to DC power when on-site generation or storage is insufficient to meet the demand within the home [11].

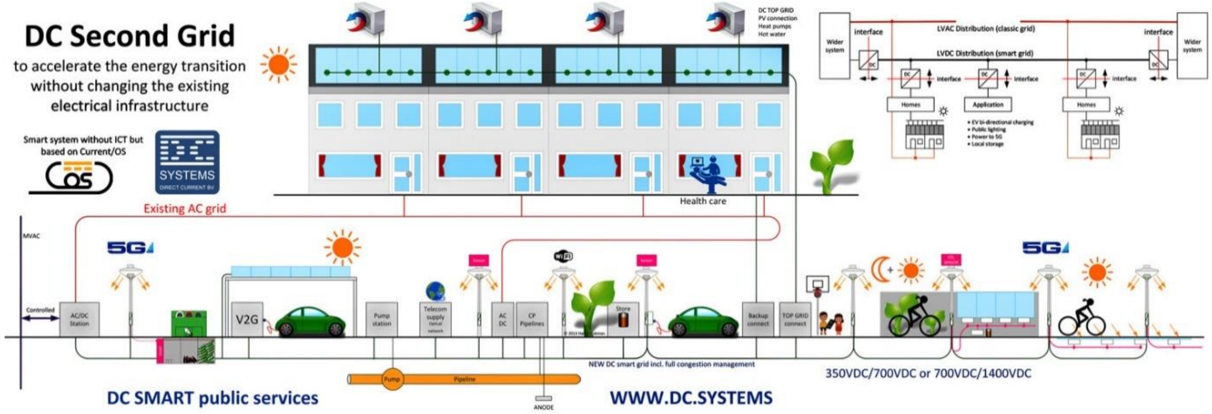

Figure 37. Hybrid DC grid [5]

Within hybrid systems, there are various approaches to structuring a microgrid and they are mainly case-based. For the installation of a DC microgrid in an existing household, it requires DC loads, power converters where needed, wiring and some form of control. However, in houses that are yet to be build, a DC microgrid could be implemented from scratch. The following hybrid cases refer to the introduction of a microgrid in existing houses. In the following examples of hybrid microgrids, a bi-directional inverter is introduced, to either convert the excess DC generation from the PV or to supply energy from the grid when there is a shortage of it. Furthermore, these systems can be called Nanogrids as they are part of the AC & DC microgrid. Here are several configurations that refer to a Nanogrid:

- DC garages:
  The rising popularity of electric vehicles, driven in part by increasing gasoline prices, has led to the development of home chargers for convenient vehicle charging. One idea to optimize the charging process involves isolating the garage from the AC microgrid of the house and transforming it into a dedicated DC grid. This arrangement eliminates the need for frequent power conversion when charging the car on a daily basis. In addition to electric vehicle charging, this garage-based DC microgrid can also power other devices like an e-boiler, having the advantages of the dedicated DC power system for efficient and integrated energy management within the garage space.
- DC-Lightning:
  It is possible to connect all lighting fixtures to the DC microgrid, as illustrated in Figure 19. DC lighting systems are already available, commonly utilizing 24 or 48 V DC to distribute power to lighting devices in alignment with the EMerge Alliance's "Occupied Space Standard [97].

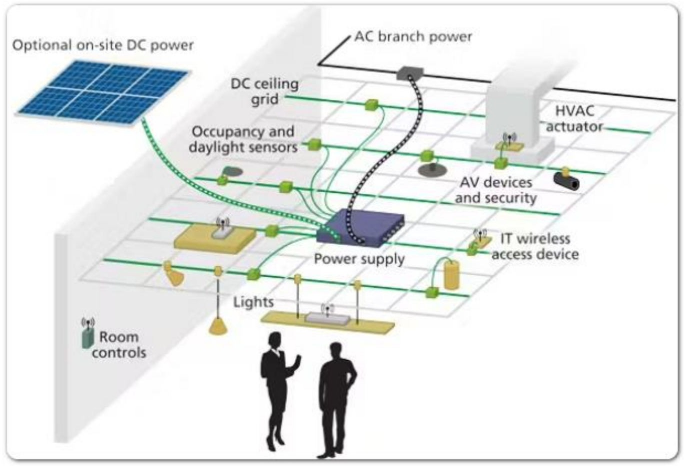

Figure 38. Lightning DC Nanogrid [97]

- DC pumping system: The sizing of a DC pumping system varies depending on its intended application. A DC water pumping system can serve purposes ranging from watering a garden's flowers to supplying water for the entire house. The size of the system is directly influenced by the energy availability, primarily derived from photovoltaic (PV) sources, that the household can harness.
- DC home security system and alarm system: A DC system integrated into a house can offer independency from the AC grid. That is why it is ideal for home security systems, as it can ensure continuous operation even during power outages. The DC-powered alarm system can include motion sensors, door/window sensors and surveillance cameras that are all directly connected to the DC microgrid.

To summarize, the implementation of hybrid microgrids depends on specific use case, including current infrastructure as well as desired goals. Optimizing the configuration to achieve a goal depends on considerations such as the existing AC infrastructure, intended applications, geographical location, and investment possibilities.

4 DC-households

This chapter answers the question "Which devices currently on the market are suitable to be used in an LV DC grid? (AC and DC devices), and which devices are in development?"

Commercial DC housing is still not a reality. Figure 39 presents a ranking of the applications that are most inclined to adopt DC distribution systems. This ranking was established by surveying a group of 32 experts in the field, all of whom are based in the United States and come from diverse backgrounds, including research institutions like universities, national labs, and industry research institutes. Many of these expects were selected through their participation in Emerge Alliance [98].

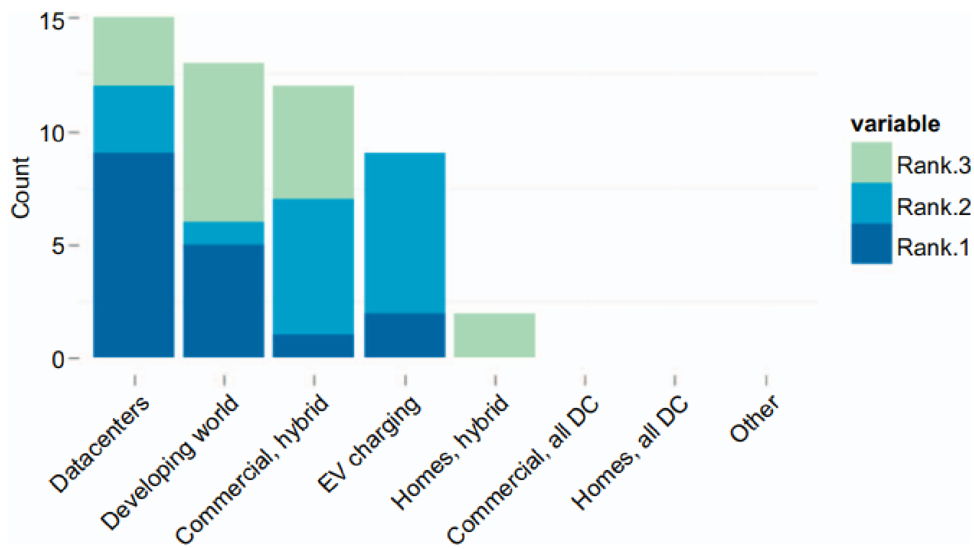

Figure 39. Ranking results of applications most likely to adopt DC distribution systems [98]

4.1 Currently Available

As it was previously mentioned, there is a lack of regulation and standardization in the application of DC microgrids in residential areas. This results in varying DC bus voltage levels across the globe, ranging from 12V to 400V in residential areas [99] and up to 1500V in industrial applications [91]. Nevertheless, as it was previously mentioned, the Netherlands is among the first countries to establish a voltage bus regulation of 350V [100]. However, most of the DC home appliances operate either with 12V, 24V or 48V, so a DC-DC conversion is needed. The following table depicts some of the commercialized DC load appliances that you can find in a home, with their power ranges and rated voltages. Note that the power ranting fits productive capacity of the application they are meant to fulfill.

Table 3. Voltages ratings of home DC appliances [99]

Home appliance	Power range [W]	Rated voltage [V]		
		12	**24**	**48**
Led lamp	5-40	X	X	X
Fan	2.7-15	X	X	
Air conditioner	816		X	X
Freezer	40-100	X	X	X
Refrigerator	40-200	X	X	X
Microwave	660	X		
Computer	16-27	X	X	
TV	5.5-24	X	X	
Washing machine	70	X	X	
Cloth dryer	40-50	X	X	
Iron	150	X	X	
Hair dryer	180-400	X		

4.2 In development

The development of new DC appliances and technologies has brought about possibilities for improved energy efficiency, integration of renewable energies and advancement DC microgrid. The following paragraphs collect some of the DC new technology that is being developed:

- Power over Ethernet:

Power over Ethernet (PoE) is a technology that enables the transmission of both power and data over a single Ethernet cable that is commonly used in network infrastructure. Over time, this technology has gone from providing only 15W to 90W. This evolution has expanded the range of devices that can be powered and connected through PoE [101]. This technology can be integrated in smart building systems, offering a centralized control, monitoring and scheduling capabilities. For instance, the lightning of a household can be powered by this technology and can be turned on or off whenever the inhabitants wishes to.

- Smart Electric Vehicle charging:

While EVs offer the advantage of reducing dependence on fossil fuels, they introduce a new set of complexities. One of the main challenge of Electric Vehicles is in fact their best feature: the electrification of the vehicle. Unlike traditional vehicles, EV owners often recharge their vehicles when they return home from work, coinciding with a period when solar energy production is limited. To mitigate this challenge, the concept of smart charging has gained popularity. Smart charging encompasses three main approaches [102]:

-V1G (Unidirectional controller charging) where vehicles are able to adjust their rate of charging depending on the grid's energy availability.

-V2G (Vehicle-To-Grid) where smart grid controls vehicle charging and returns electricity to the grid, this bidirectional flow can enhance grid stability.

-V2H/B (Vehicle-To-Home/Building), where vehicles will act as supplement power suppliers to the home providing the stored energy back to the grid when there are peak demands.

However, combining energy efficiency with the behavior and preferences of individuals can be a challenging task. The efficient utilization of EVs as energy resources requires understanding the occupants' lifestyles, charging patterns, and energy demands.

- DC-based home appliances that replace AC-inherent appliances:

In a DC microgrid, it is advantageous to have all consumers compatible with DC power consumption. However, certain home appliances are designed exclusively for AC power. Nonetheless, advancements in technology have provided with equivalent DC-based home appliances. The table below highlights a selection of these replacements [103]:

Table 4. DC technologies that can be used to replace old AC appliances

Appliance	AC-technology	DC-internal technology
Lighting	Incandescent	Electronic(fluorescent)
Cooking	Electric resistance	Induction
Home electronics	Digital electronics	Digital electronics
Heating	Electric resistance	Variable-speed drives driven by brushless DC permanent motos
Cooling	Induction motor, single speed compressor	Variable-speed drives driven by brushless DC permanent motos
Mechanical work	Induction	BDCPM motor

5 Modelling and Simulation of DC grids

This chapter details the model created in order to investigate DC grid related questions, such as how different components of the microgrid perform in AC or DC grids and examining characteristics such as voltage, current, losses and conversion efficiencies. The research questions answered is ‘What is the architecture of a DC grid model, and how can this be constructed?’

5.1 Model Introduction

As part of this projects goals of supplying tools with which both researchers and students can investigate DC grid related problems, including comparisons to AC grids, a model is needed. Therefore, a model was developed in MATLAB SIMULINK [104]. The topology of the model is the recreation of the existing microgrid of the Tinylab, see Figure 40 and Chapter 6. The model itself is a product in WP6, to be used both standalone (to investigate relevant scenarios) as well as in combination with the Tinylab testing environment (to verify that lab functions as expected).

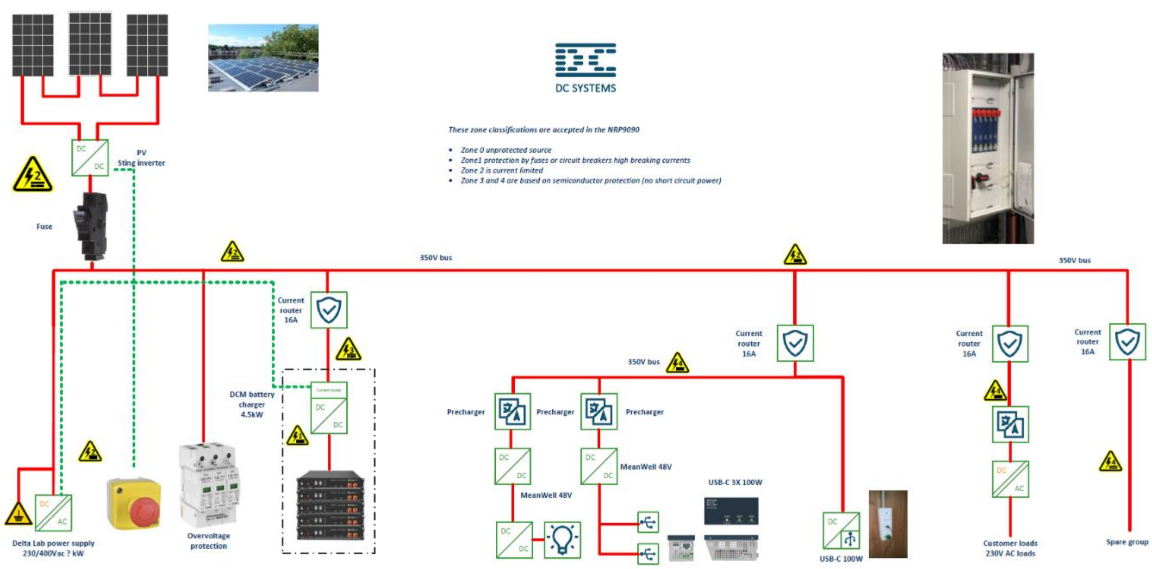

Figure 40. Tinylab microgrid

The following components and their relationship are modelled in order to answer the main question of this chapter:

- Grid connection (GRID),
- Energy storage system (ESS),
- Load (LOAD),
- PV panels (PV),
- AC/DC and DC/DC Converters (Inverter, Buck, Boost, Rectifier).

5.2 Model Requirements

The following requirements were established to bring the scope and boundaries to the model. Using MoSCoW method [105], these requirements are then categorized by priority.

Table 5. Model Requirements

Req. Number	Requirement	Priority
1	There is a simulation model of a DC microgrid.	M
2	There is a simulation model of an AC microgrid.	M
3	The model needs to include the DC/DC or AC/DC conversions (based if it is an AC or a DC microgrid simulation.	M
4	The model needs to have inputs (i.e. Solar data and load data).	M
5	The model is a discrete model.	M
6	The model needs to include cable impedances.	C
7	The grid connection of the model is bi-directional	S
8	The model needs to have logic, control method.	M
9	Each component needs to be designed to emulate a component in a Tiny Lab.	S
10	There is energy storage system in the model.	M
11	There is PV panels in the model.	M
12	The microgrid of the model has a grid connection.	M
13	The model has a load.	M
14	The load has an input.	M
15	The PV panels have an input.	M

5.3 Model Topology

Two model topologies are used for this simulation. First one focuses on the DC microgrid with the aim to establish where the DC/DC converters are and what their conversion efficiencies are. Second model focuses on the same grid but with a major distribution line of AC instead of DC. Using both modules it is possible to find how would then the conversion and their efficiencies perform.

Figure 41 shows both the DC and AC microgrids model topology with inputs, components and where converters are placed.

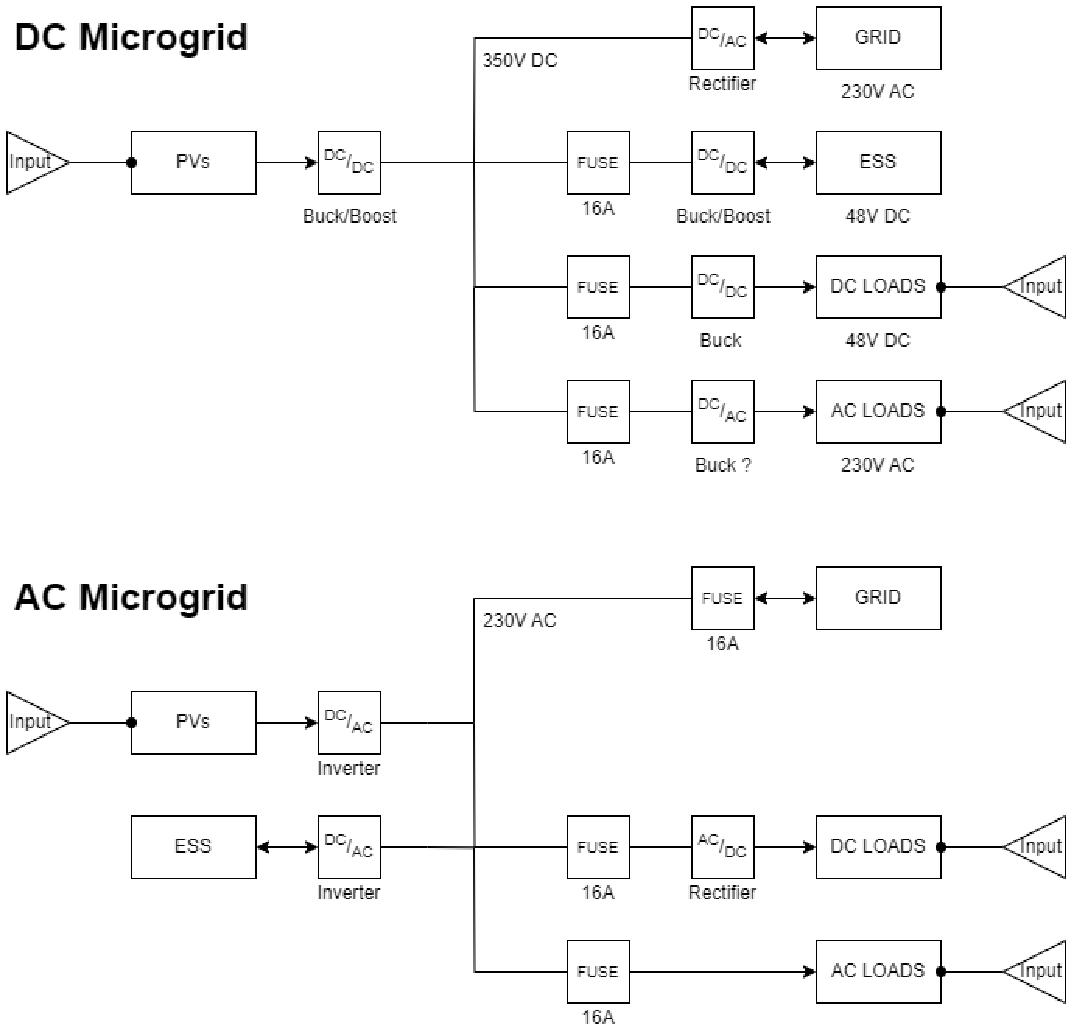

Figure 41. AC and DC microgrid topology

5.4 The Model

First, a functional description of the model followed by a technical one are examined at in this part of the chapter. Each component of the model was built using the SIMSCAPE addon library in MATLAB SIMULINK. The following subsections discuss the individual components, their inputs and settings. Finally, a total overview of the model is given.

5.4.1 Model Control

In order for the simulation to work properly, a control has to be implemented to determine which component is used, when and under what conditions. Figure 42 below shows the black box inputs and outputs of the simulation.

Figure 42. Model inputs and outputs

Figure 43 shows the functional control of the model, which uses imbalance calculation as its main control/priority algorithm.

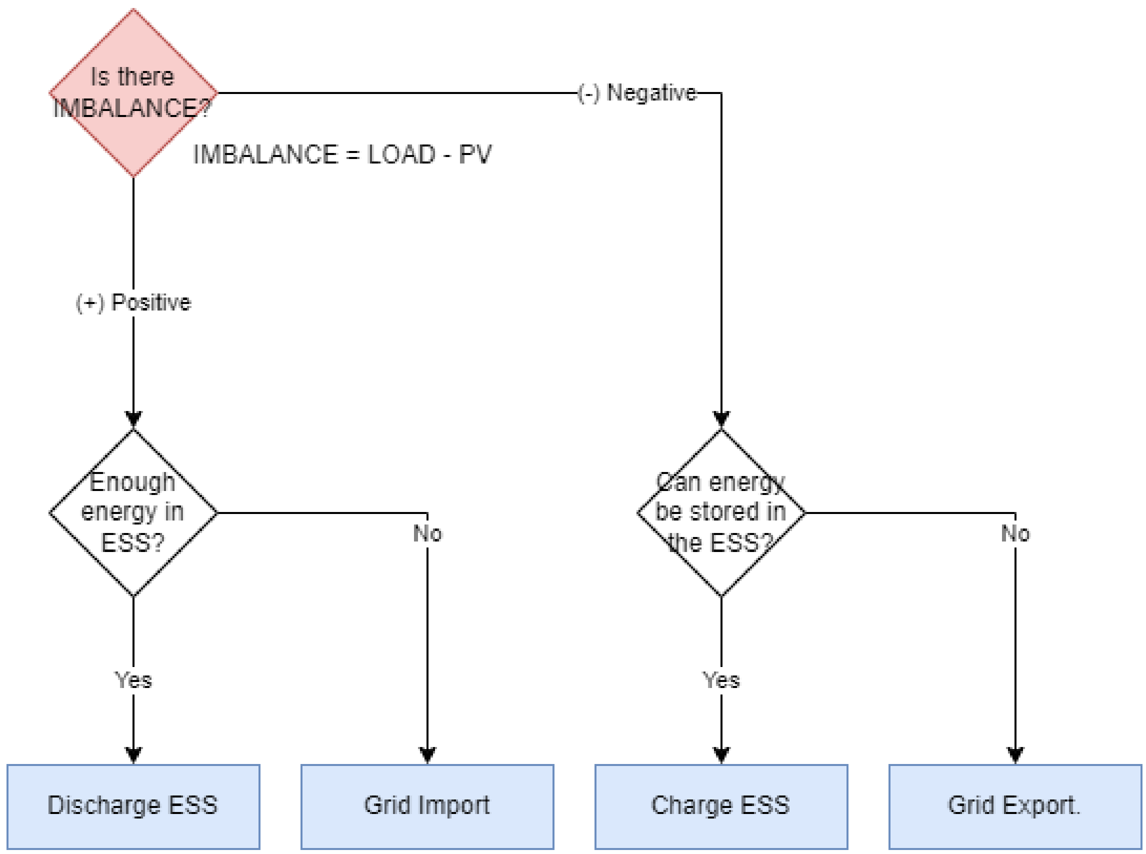

Figure 43. Model Controller Functional Diagram

Curtailment is neglected as an option, but this is something that can be studied in the future work. In this model, there is no difference between grid export and curtailment. Furthermore, Figure 44, shows a technical overview of the control, which was implemented in MATLAB SIMULINK. For this, the functional flow was transferred towards a state-based logic, depending on the functional flow some components are either ON or OFF. The load and PV are static components. They are not controlled.

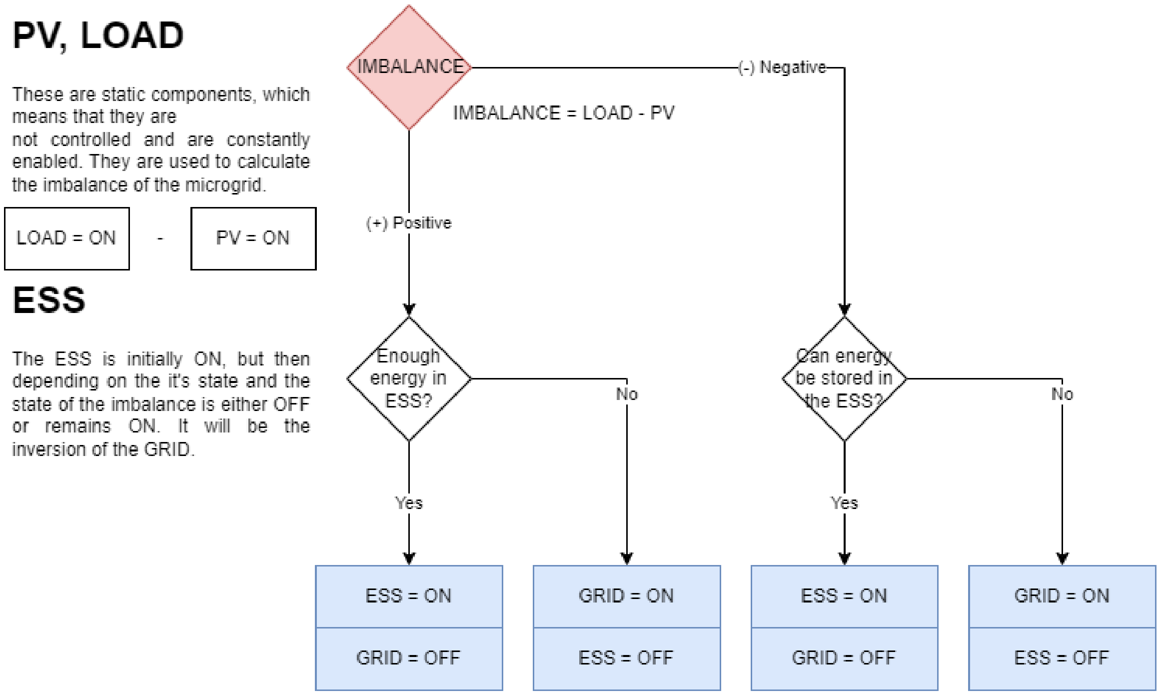

Figure 44. Technical model controller

In MATLAB SIMULINK, the process of replicating the control involves the initial creation of an imbalance calculation. This calculation serves the purpose of evaluating whether the Energy Storage System (ESS) is being charged or discharged. Figure 43 illustrates the visual representation of the imbalance calculation, while Figure 44 portrays the control mechanism for charging the ESS.

To carry out the calculation, voltage and current from both the load and the photovoltaic (PV) sources are utilized. Power is then computed by multiplying voltage times current. The calculated power values are employed to determine the imbalance, which is represented as the difference between the load and PV power: IMBALANCE = LOAD - PV.

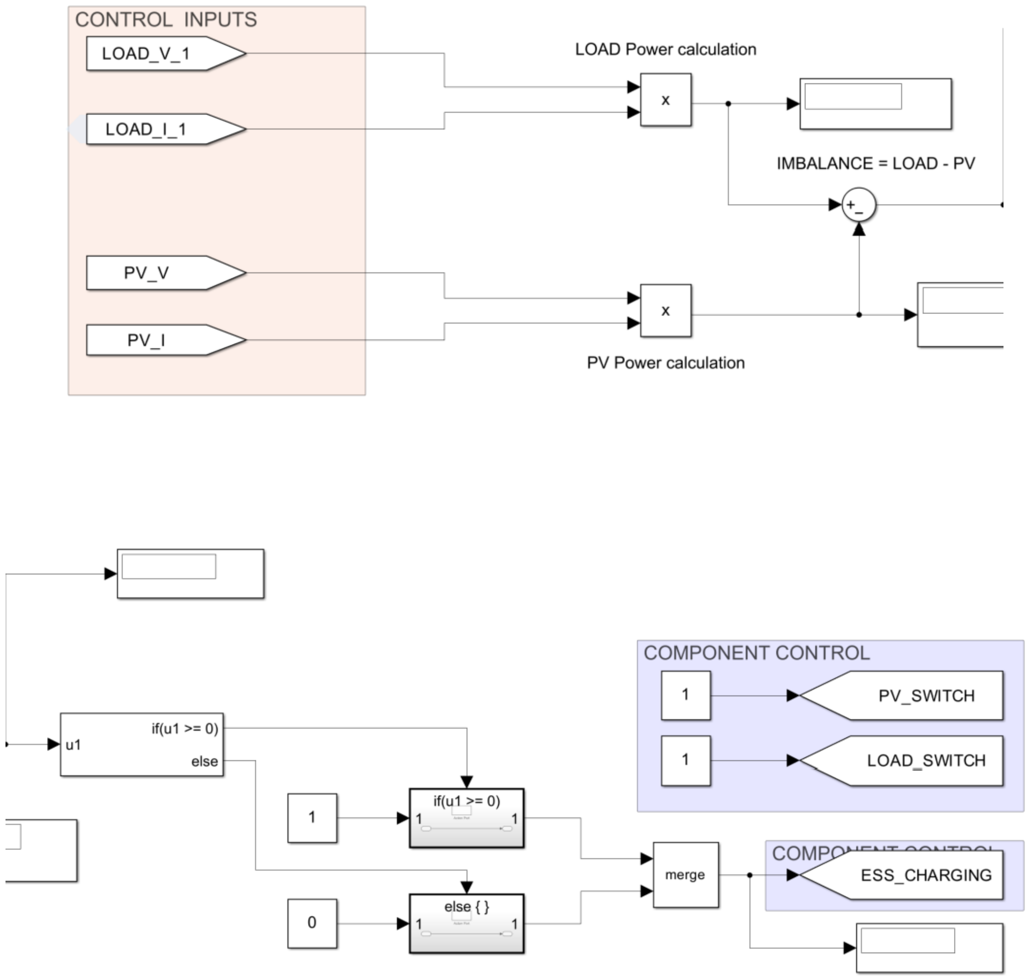

Figure 46. Control Charge/Discharge

Using an IF block in SIMULINK, a state of the ESS is then determined, ESS_CHARGING. This is a Boolean state, meaning it is either ON or OFF. As mentioned previously, LOAD and PV are static components. They are not controlled, or controlled manually by the user if there is need. Next, using the imbalance, it is then determined which of the remaining components is enabled or disabled. In Figure 45, an IF block is used once again (circled in red) inheriting its functionality from the technical diagram. The IF block determines the working in this part of the model based on inputs and what is happening in the rest of the model, primarily monitoring the State of Charge (SoC) of ESS.

Block's inputs are: SoC value and Boolean value of ESS_Charging.

The following statements are implemented, values can be adjusted for flexibility of the model:

- IF ESS is CHARGING and SoC of ESS is more than or equal to 5%,
- IF ESS is CHARGING and SoC of ESS is less than 5%,
- IF ESS is NOT CHARGING and SoC of ESS is less than 100%,
- IF ESS is NOT CHARGING and SoC of ESS is more than or equal to 100%.

Each state then determines if ESS and GRID components are enabled or disabled, refer to the technical control diagram, above.

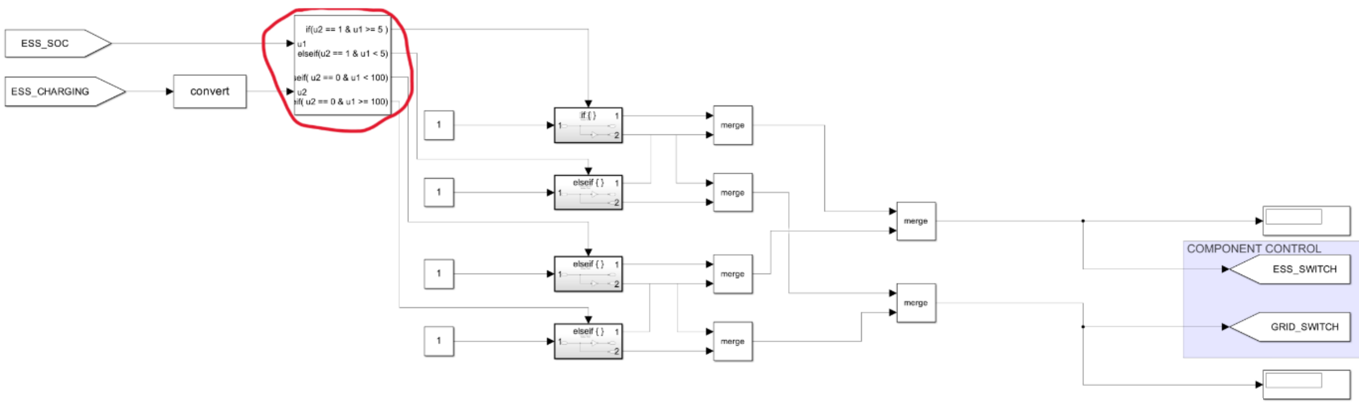

Figure 47. Component control

5.4.2 GRID Component

Figure 48 shows how the grid connection was designed in the MATLAB SIMULINK. The GRID connection consist of the following, from right to left: AC Source, Linear Single phase transformer, a rectifier which is connected to the Inductor and a parallel connection with a Capacitor. Two voltage meters are attached to measure the AC input voltage and DC output voltage. At the end, a switch is added that allows the controller, discussed before, to enable/disable this component. Furthermore, the AC Source is set to 230V AC and 50Hz frequency, which is the standard low voltage grid specification for Europe. Also, the linear transformer is set to take 230V on its primary side and converter it to 350V on the secondary side. Transformer is set to be ideal, so no resistance or inductance. However, these values can be modelled in further to increase the accuracy of the simulation. Finally, the signal is still AC and needs to be converted to DC, which is why a rectifier, inductor and a capacitor are added to the model. The capacitor and inductor values are also set to an ideal situation and further research has to be done to achieve a more realistic DC signal.

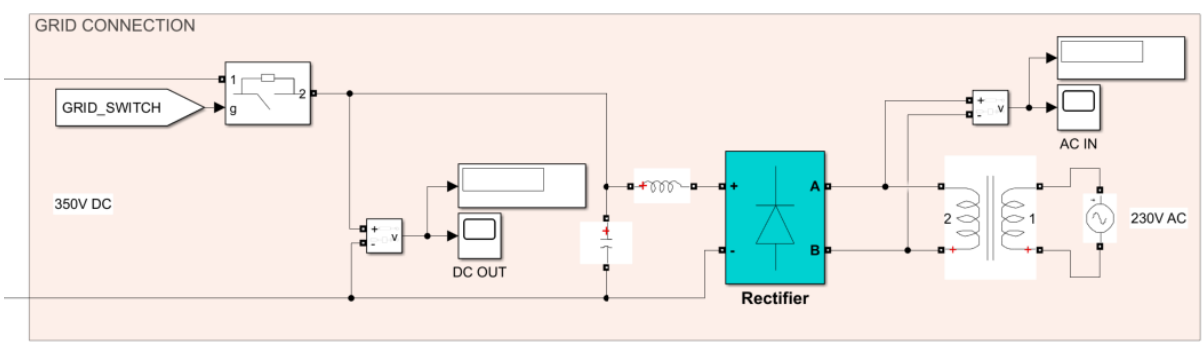

Figure 48. Grid connection MATLAB

5.4.3 Energy Storage System Component

Figure 49 shows how the energy storage system was designed in the MATLAB SIMULINK. There is a specialized block that is present in the MATLAB SIMULINK SIMSCAPE library.

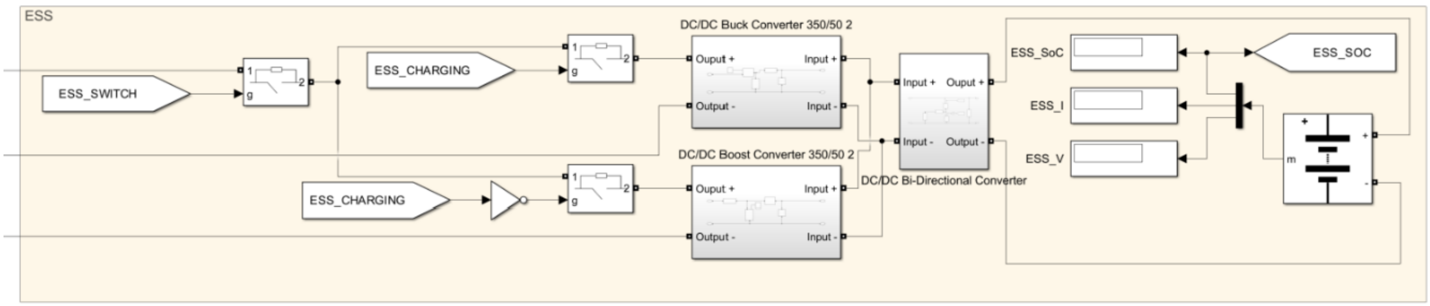

Figure 49. ESS in MATLAB

Additional components are required, specifically converters, which are discussed below, which allow the battery to convert its voltage requirements based on whether it is CHARGING (Buck converter) or DISCHARGING (Boost converter). Which converter to use is determined by the switches, which change the current (I) path. SoC value is also monitored here for the model controller. The battery block has several settings that can be adjusted to simulate the PYLONTECH battery used in the Tiny Lab. Additionally, temperature and aging effects could be studied and applied in the block but are not part of the model at this stage of the project.

5.4.4 LOAD Component

There are two ways to simulate a load. The first is to use a simple variable resistor that can use a power data input which is then converted back to voltage, current and resistance. Data can be imported using Data Inspector, the data is then converted to a signal which can be used as an input for variable resistor block. Data cab in a CSV (Coma Separated Value) or an Excel format. The resistance values are then used each time step to simulate a load. Second way is simplistic in the implementation. It is just to use a static resistor (RLC load block in SIMULINK) with a set voltage and power setting.

At this stage of the project RLC load block was used. Figure 50 demonstrates the RLC load component with its settings. These settings are set to simulate a simple DC load of around 1500W at around 50V DC. Load can be duplicated and added to the model to simulate various loads that are present at the Tiny Lab.

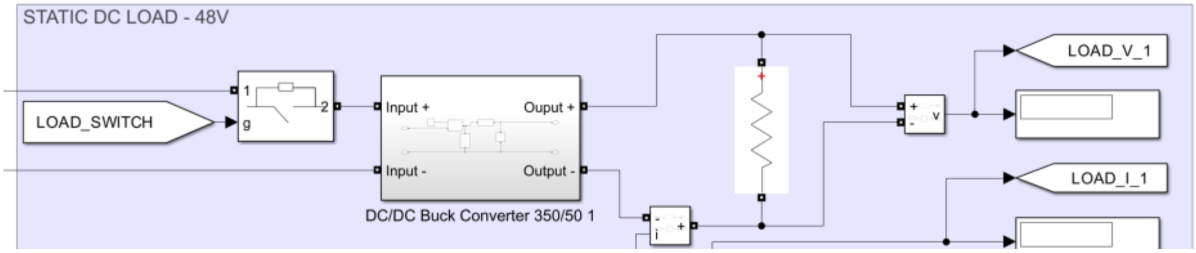

Figure 50. Load MATLAB

5.4.5 PV component

Similar to ESS component, SIMULINK library also has a specialized PV component. This component is used and can be seen in Figure 51 (highlighted in blue). Additionally, a boost converter is used to increase output voltage. A switch is also added which allows manual enable/disable control over the component. Voltage and current meters are also added here to send back the values to the model controller.

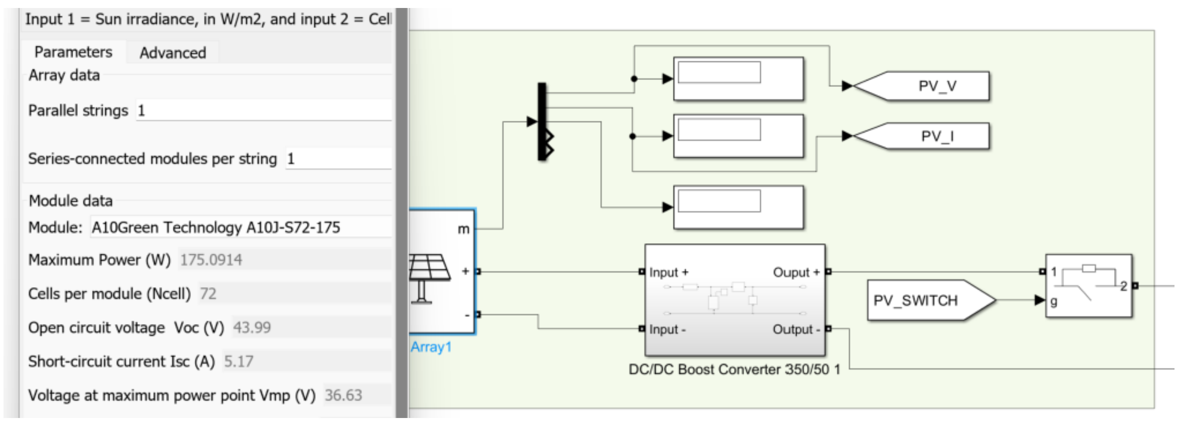

Figure 51. PV Panel MATLAB

The block uses Irradiance and Temperature values as its inputs. This block then can be further edited to simulate a variety of PV panels, specifically panels used at Tiny Lab.

5.4.6 Converters

There are several types of converters used in this simulation: rectifier, buck, boost, inverter.

1) A rectifier, which is used to convert AC signal to DC:

- DC microgrid: part of the GRID component, see subchapter 5.4.1,
- AC microgrid: part of the LOAD component, specifically DC loads.

2) Buck converter, Figure 50, used to step DC voltage down, i.e. from 350VDC to 50VDC (LOAD and ESS),

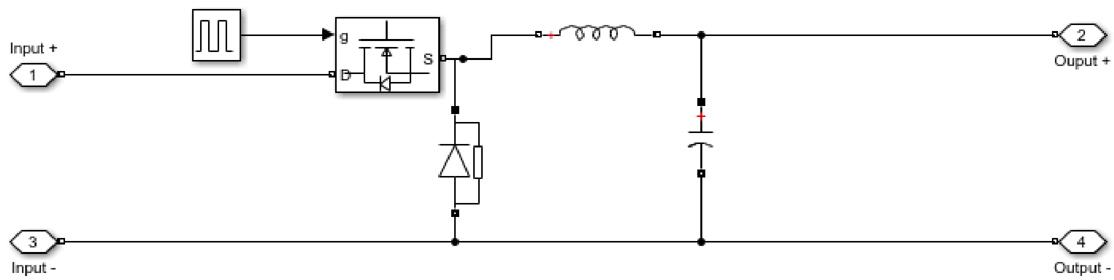

Figure 52. Buck converter

Buck converter consists of the following components in the model (from left to right): Pulse generator, which is connected to the MOSFET, a parallel Diode connection, and inductor in series with MOSFET, and a parallel capacitor.

The following settings are used for the buck converter:

- Both MOSFET and Diode use pre-set values,
- Duty cycle = 0.13714286, used in the pulse generator,
- L = 0.00002247,
- C = 0.00060252.

3) Boost converter, Figure 53 used to step DC voltage up, i.e. from 50VDC to 350VDC (PV and ESS), Consists of the same components as Buck but the layout is different.

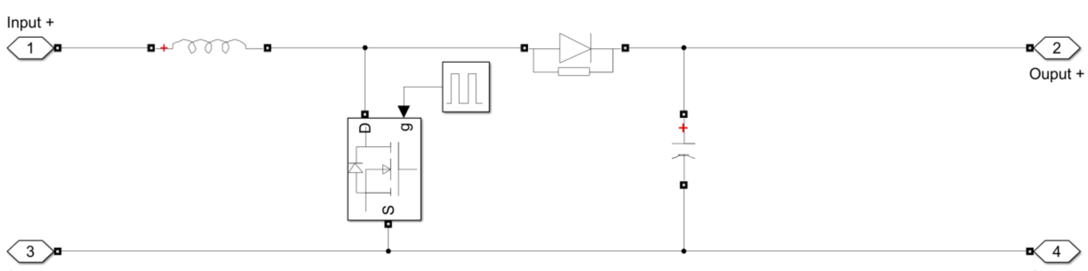

Figure 53. Boost converter

The following settings are used for the boost converter:

- Both MOSFET and Diode use pre-set values,
- Duty cycle = 0.86285714, used in the pulse generator,
- L = 0.003,
- C = 0.00003.

4) Final converter is an inverter. It is used to convert the DC signal to AC signal, used as part of ESS component in an AC microgrid. Figure 54, from [106], shows the inverter structure.

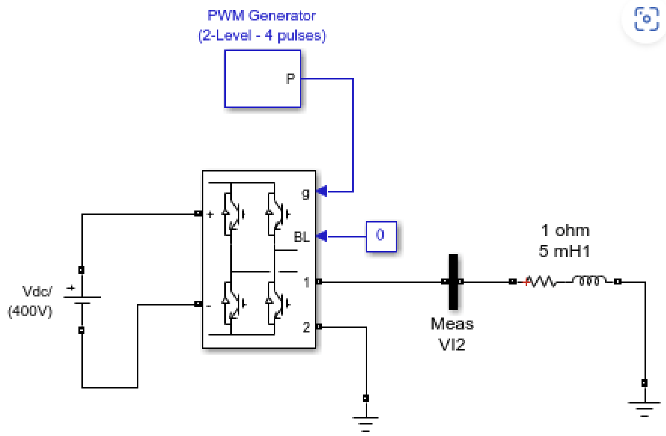

Figure 54. Inverter

5.5 Scenarios

Scenarios are needed with which to conduct simulations. As such, two model setups were designed. The results of these two models are compared. Th model topology, shown previously, showcases these models and their structure.

Scenario 1, baseline run of the modelled microgrids (AC and DC).

- No LOAD,
- No PV,
- No model controller.

Scenario 1 is run several times (3-5) for calibration purposes.

The goals: to test the GRID and ESS components and their performance; to record the conversion efficiencies of each converter in both models; to compare the baseline AC and DC total conversions.

Scenario 2, simple run.

- Adding DC STATIC LOAD,
- Adding PV,
- Model controller is added.

The goal: to test the model controller; to record the conversion efficiencies of each converter in both models; compare the AC and DC total conversion.

Scenario 3, advanced run.

- Adding advanced DC LOAD, with a power profile,
- Adding power profile to the PV,

The goal: to test the inputs with proper profiles gathered from the monitoring systems at the Tiny Lab; to record the conversion efficiencies of each converter in both models; compare the AC and DC total conversions and also compare to the real recordings, if present. This is done for final model validation.

Each scenario is run 3 times to calculate an average result with an error scale.

5.6 Results Analysis

After several baseline simulations, it was established that the designed buck and boost converters do not work as intended. Due to this conversion, efficiencies are not possible to establish. The buck and boost converters do not work with the current input values. Figure 55 shows the DC output out of the GRID connection that flows to other components. Here, it is shown that the converter output is not a stable value, but oscillates between around 200 V and 500 V. This is in part due to enabling the gird connection, which when enabled is not stable and the DC part goes above set 350V DC at the transformer. At 3.7 seconds, the GRID is enabled through the controller and the DC voltage starts to oscillate. Furthermore, the rectifier and it's component have to be adjusted further. Due to this, further model converters are also not stable. Finally, both the PV and the ESS have to be setup to accurately model the Tinylab components, in order to establish a baseline functionality. This is not possible at present due the components availability.

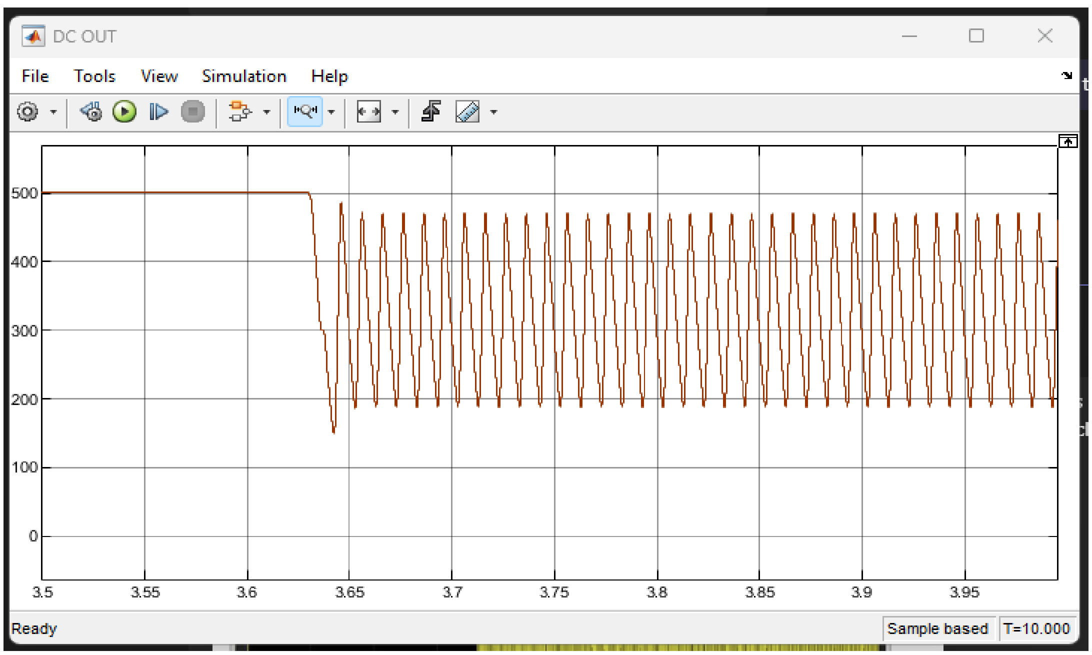

Figure 55. DC Rectifier Voltage Out

5.7 Model conclusion and recommendations

5.7.1 Conclusion

Although the model was designed, its performance is unstable due to problems with converters and rectifier. The goal for continuation is to look deeper into AC/DC and DC/DC converters. Hence, at this moment the main question cannot be answered.

Components have been designed. The model of DC microgrid has been designed. The final product is built. This model will be used together with education to further the DC grid knowledge among the students.

Below is the table of requirements that are met and all components of the model that are created. The following requirements have been met:

Table 6. Requirements met of the model

Req. Number	Requirement	Priority	Checklist
1	There is a simulation model of a DC microgrid.	M	✓
2	There is a simulation model of an AC microgrid.	M	✗
3	The model needs to include the DC/DC or AC/DC conversions (based if it is an AC or a DC microgrid simulation.	M	✓
4	The model needs to have inputs (i.e., Solar data and load data).	M	✗
5	The model is a discrete model.	M	✓
6	The model needs to include cable impedances.	C	✗
7	The grid connection of the model is bi-directional	S	✗
8	The model needs to have logic, control method.	M	✓
9	Each component needs to be designed in way that it can emulate a component in a Tiny Lab.	S	✓
10	There is energy storage system in the model.	M	✓
11	There is PV panels in the model.	M	✓
12	The microgrid of the model has a grid connection.	M	✓
13	The model has load.	M	✓
14	The load has an input.	M	✗
15	The PV panels have an input.	M	✗

The component checklist:

Component	Checklist	Comment
GRID	✓	Bi-directional path and controll needs to be added.
ESS	✓	Settings need to be changed to emulate the battery stack in the Tiny Lab.
PV	✓	Settings need to be changed to emulate the panels in the Tiny Lab.
DC STATIC LOAD	✓	Basic load, it is a static value, can simulate a device.
DC VARIABLE LOAD	✗	To simulate a profile.
AC VARIABLE LOAD	✗	To simulate a profile.
BUCK CONVERTER	✓	Needs re-work.
BOOST CONVERTER	✓	Needs re-work.
RECTIFIER	✓	Needs adjustment to simulate the proper conversion values.
INVERTER	✗	Not implemented. Needs to be designed.

5.7.2 Recommendations

The recommendations for the requirements are as follows:

1) Requirement 2, AC microgrid model is partially designed. It needs an inverter. A recommendation is to use SIMULINK to create a similar component. SIMULINK has some tutorials on inverter converters that can be used to create this.
2) Requirement 4, how to import data has been looked at. However, what is left is to implement the import and conversion to proper signals. A workflow and some calculations are briefly discussed in the subchapter about LOAD Component.
3) Requirement 6, cable losses are not implemented. However, to further study the conversion impedances and the potential losses of AC and DC microgrids this needs to be implemented. A resistor can be added and edited between the component to emulate this.

4) Requirement 7, the bi-directional part of the grid can be re-created using same connection as in ESS component. Additional control values and additional control needs to be added to the GRID component to implement this.
5) Requirements 14 and 15, the recommendation is referred to point 2, above.

Outside of the requirements, there are the following recommendations:

1) Several components (i.e., transformer, capacitor and inductor) are using ideal values, this affects the results of the model. Obtaining the precise values for these components without access to the Tiny Lab proves to be challenging Hence the recommendation is once the lab is running to monitor similar components and record their performance, use the data to modify the simulation components.
2) Currently there is no difference between the grid export and curtailment. Curtailment is being neglected conceptually but should be studied in the future work and model development.
3) Rectifier component has to be adjusted to produce a stable DC output.
4) Both Buck and Boost converters have to be adjusted to produce stable step up/down DC voltages.

6 Implementation of the Smart Tinylab DC grid

7 Conclusions and Further Research

7.1 Conclusions

In conclusion, WP6 of the Tinylab project had a number of subgoals. A description of each goal and the outcome is given below:

(I) *To realize a practical laboratory for testing a local DC grid and new DC components in a user situation and the ability to compare the performance of a DC grid with DC devices to an AC grid with AC devices.*

The Tinylab practical laboratory was realized at detailed in Chapter 6. The lab does have the ability to compare DC and AC grid performance with a number of relevant devices.

(II) *To gain insights from the laboratory regarding technical performance, user experiences, and safety aspects of DC grids in relation to AC grids for further development.*

Unfortunately, due to the delay in the construction of the DC grid in the Tinylab, no practical testing regarding performance, user experiences or safety was possible within the project period. However, technical performance and safety were explored in literature (see Chapters 2, 3 and 4), giving us much insight into the workings of DC grids. Furthermore, and more importantly, it gives us a starting point for future practical investigations with the Tinylab.

(III) *To contribute to the (inter)national knowledge and experience with DC grids for residential and office buildings.*

The knowledge and expertise gained during this project are beneficial to the development of DC grid in the Netherlands. This includes both DC grids more generally as well as residential cases. This benefit is twofold. First, researchers in both industry (the project consortium) as well as at Saxion now have a better understanding of the functioning of DC grids as well as their possible future applications. This leads to DC grids being considered as feasible solutions within future projects. Second, researchers and lecturers at Saxion are now able to add more about DC grids into the curriculum. This allows Saxion's students, especially in the Electrical and Electronic Engineering department, to learn more about DC grids, and take this knowledge into their future careers, which will allow more DC grid projects to be considered in the future.

(IV) *To contribute to the component development and market proposition of partners (DC component suppliers, DC installation companies) through practical research*.

As with goal II, the lack of time for practical research has led to this goal not being achieved. However, the challenges faces when installing the DC grid in the Tinylab have aided Eaton and Microgrid Solutions in furthering their own knowledge about DC grids. In this respect, the goal was achieved.

Furthermore, a number of research questions were posed. Below are short answers to each question.

1. *What active control is possible for DC grids?*

   Active control is possible through the use of controlled power electronics in DC grids. Hereby, Active Front Ends (AFE) are critical for the AC/DC grid connection. Furthermore, DC grids can either be in grid connected or islanded mode, where either power is exchanges or (temporarily) not exchanged with a connected (often times AC) grid. Finally, a number of grid control strategies were examined, including centralized, decentralized, distributed and hierarchical. Current/OS was discussed as an example of a protocol developed in the Netherlands and currently on the market.

2. *What are the components and techniques necessary in order to have an LV DC grid system, which can be connected to an existing AC LV/MV grid?*

   Power electronics are critical components within LVDC systems. These include rectifiers (AC/DC), inverters (DC/AC) and different types of DC/DC converters including buck, buck-boost and the more widely used in DC grids Dual Active Bridge (DAB) converter. Furthermore, storage and power generation and/or grid connections are required. Storage is needed to increase the flexibility of the system and balance any power imbalances. PV is needed for a native DC power supply, while a connected electricity grid, usually AC, can also be used. Finally, loads which can either be used directly in DC (such as computers and microwaves) or converted (such as most washing machines).

3. *Which devices currently on the market are suitable to be used in an LV DC grid? (AC and DC devices), and which devices are in development?*

   A number of devices were found to be DC compatible, see also the answer to question 2. Furthermore, power over ethernet, Electrical Vehicle (EV) charging and more traditionally AC household devices (such as washing machines and heating) have DC versions currently in development.

4. *What is the architecture of a DC model, and how can this be constructed?*

   A DC model was discussed in depth in Chapter 5, including the model requirements and topology. This architecture includes power electronics, loads, energy storage and solar PV generation. It was constructed in MATLAB SIMULINK.

5. *Which AC and DC household grid designs are considered feasible?*

   One grid design was analysed in more depth, the AC/DC grid design. This is considered feasible in the Netherlands as it both reduces the need for power conversions in a household (only DC/DC) as well as makes use of the existing AC grid to meet household power needs when the DC grid generation and storage capabilities are insufficient. The DC grid can therefore be considered a side grid to the main AC grid. Furthermore, so called Nanogrids (smaller systems within a microgrid infrastructure) are feasible in the form of DC garages, DC lighting, DC home security systems and if needed DC pumping systems.

6. *Which technical challenges, including safety, do DC grids have?*

A number of technical challenges were investigated, including different types of faults (grounding, current, no zero crossing). Furthermore, the IEC TS 60479-1-2026 standard was analyzed. Also, the classification of dangers based on current and voltage were examined, in order to establish what is relevant for LVDC.

In summary, the goal of WP6 to research, develop and test a LVDC grid in the Tinylab was partially a success. Although research and development were achieved and a working LVDC grid was realized, the grid could not be practically tested other than to confirm correct installation. However, this project can be considered a success, as knowledge was gained, most of the sub goals were achieved and a number of relevant research questions were answered. This information is not only useful to researchers but also to teach students. As a main lesson learned, in the future development of a DC grid pilot, the planning should not be too optimistically planned, especially as part of a large project with other goals and work packages. In other words, more time for development and installation should be taken, in order to guarantee enough time to do the physical testing.

7.2 Further Research

As a result of the research conducted, a number of recommendations for further research are:

- The model requires re-evaluation and further development. Although large steps were made in the creation of the model, it does not yet function as required. Several components need to be retested and then re-integrated into the model, while being tested that they function correctly. Furthermore, the requirements which were not met need to be re-assessed.
- The model requires validation in combination with the Tinylab setup. Most of the values used in the model are (near) ideal, and in practice they will not be an accurate enough reflection of the Tinylab to gain insights into its functionality. Therefore, the real world components that were used in the Tinylab must also be dimensioned accurately in the model. Furthermore, curtailment should also be added as an option for both solar PV as well as certain loads, in order to more accurately model what can generally be controlled in active microgrids.
- Further exploration of DC grid control strategies is needed. In order to gain a better understanding of which control strategies are useful in certain situations, relevant strategies should be tested both in the model (and must therefore be recreated in the model) as well as in the Tinylab itself. This investigation should include but not be limited to Current/OS, as it appears to be the prevalent strategy which will be used in the Netherlands in the coming years.
- A practical comparison using the Tinylab between AC and DC in several current and future scenarios is needed. This includes a simulation study. The scenarios should include both residential, office and industrial cases, where DC grid technology is considered promising. Although this report can be used as a general guideline to evaluate promising scenarios, a more in depth analysis before the study would be useful, in cooperation with potential DC grid users.
- A detailed practical investigation into the user experiences regarding DC grid interactions is needed. This can be done with the Tinylab. This step is critical in order to gauge user acceptance of DC grids in households especially, and specifically to investigate what barriers to user acceptance need to be overcome before a wider range rollout is feasible in the Netherlands.

- As an extension of the user experience point, a practical safety analysis of the Tinylab is required. This would evaluate more practically what safety issues (if any still exist), which would need to be addressed before a wider range rollout is feasible in the Netherlands.
- DC grid theory should be more fully integrated into the curriculum of Saxion, especially (but not limited to) the Electrical and Electronic Engineering department. This must be discussed with the lecturers of the relevant courses (e.g., power electronics, power systems and network related courses). In addition, the Tinylab should be used as a test environment so as to give students a practical understanding of how DC grids function. The model can be used in order to gain a more theoretical understanding.

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