Bachelor's thesis

Energy and Environmental Technology

2022

Mikko Heinonen

COMPARISON OF LVAC AND LVDC MICROGRIDS

TURKU AMK

TURKU UNIVERSITY OF APPLIED SCIENCES

BACHELOR'S THESIS | ABSTRACT

TURKU UNIVERSITY OF APPLIED SCIENCES

Energy and Environmental Technology

2022 | 49 pages

Mikko Heinonen

COMPARISON OF LVAC AND LVDC MICROGRIDS

The objective of this thesis was to 1) compare the advantages and disadvantages of low voltage direct current (LVDC) technology and low voltage alternating current (LVAC) technology in microgrids, and 2) address the technological efficiency and energy savings produced by LVDC technology compared to LVAC technology in microgrids according to literature. With the intention to validate the findings regarding part two, a simulation based on a real-life case was performed utilizing the technical features of commercial solutions found on the market.

This thesis was commissioned by the New Energy research group of Turku University of Applied Sciences, which is a partner in a project called RESPONSE. RESPONSE is a five-year project funded by the European Commission's Horizon 2020 Framework Programme, and it aims to find smart, energy positive and sustainable integrated solutions for neighbourhoods and cities. For this project, a local microgrid is designed and implemented at the Turku Student Village. The technical specifications and the structure of the electrical network of this microgrid were modeled in this thesis.

The findings of part one indicate that LVDC technology has remarkable advantages over LVAC technology regarding energy and resource efficiency, control and cost-effectiveness. Among its disadvantages are the utilization of traditional protection components, and the complexity of voltage regulation and connection to the grid. The findings for part two indicate that LVDC microgrids can have 6-18 % better energy efficiency compared to LVAC. The simulation performed did not validate the findings, but it verified that the energy efficiency and energy savings of a LVDC system implemented into a LVAC system are dependent on the direct current (DC) load ratio of the system.

The challenges related to the simulations are discussed and recommendations for improvement are suggested for the future.

KEYWORDS:

Microgrid, energy efficiency, distributed generation

OPINNÄYTETYÖ (AMK) | TIIVISTELMÄ

TURUN AMMATTIKORKEAKOULU

Energia- ja ympäristötekniikka

2022 | 49 sivua

Mikko Heinonen

LVAC JA LVDC TEKNIIKALLA TOTEUTETTAVIEN MIKROVERKKOJEN VERTAILU

Opinnäytetyön tavoitteena oli kirjallisuuden pohjalta vertailla 1) matalajännitetasavirta (LVDC) -teknologialla toteutettavien mikroverkkojen etuja ja haittoja matalajännitevaihtovirta (LVAC) -teknologiaan verrattuna ja 2) LVDC-teknologian teknistä tehokkuutta ja sen tuottamaa energiasäästöä verrattuna LVAC-teknologiaan mikroverkoissa. Tosielämän tapaukseen perustuva simulaatio suoritettiin tarkoituksena todentaa kohdan 2 havainnot hyödyntäen markkinoilta löytyvien kaupallisten ratkaisujen teknisiä ominaisuuksia.

Opinnäytetyö tehtiin Turun ammattikorkeakoulun Uusi Energia -tutkimusryhmälle osana RESPONSE-nimistä hanketta. RESPONSE on Euroopan komission Horisontti 2020 -puiteohjelman rahoittama viisivuotinen hanke, jonka tavoitteena on löytää älykkäitä, energiapositiivisia ja kestäviä kokonaisratkaisuja asuinalueille ja kaupungeille. Tätä hanketta varten Turun ylioppilaskylään suunnitellaan ja toteutetaan paikallinen mikroverkko, jonka sähköinen rakenne ja tekniset ominaisuudet pyrittiin mallintamaan.

Kohdan 1 havainnot osoittavat, että LVDC-teknologialla on merkittäviä etuja verrattuna LVAC-teknologiaan energia-, resurssi- ja kustannustehokkuudessa sekä järjestelmähallinnassa, mutta sen haittoja ovat jännitteen säädön ja verkkoon kytkennän monimutkaisuus sekä perinteisten suojakomponenttien käytettävyys. Kohdan 2 löydöksien mukaan LVDC-mikroverkot voivat olla jopa 6–18 % energiatehokkaampia LVAC-mikroverkkoihin liittyen. Opinnäytetyötä varten tehdyt simulaatiot eivät validoineet kohdan 2 tuloksia, mutta ne osoittivat, että LVAC-verkkoon sisällytetyn LVDC-mikroverkon energiatehokkuus ja energiasäästöt riippuvat tasavirta (DC) -kuormien suhdeluvusta.

Opinnäytetyön simulointeihin liittyvistä haasteista keskustellaan ja parannusehdotuksia ehdotetaan jatkoa ajatellen, kuten muun muassa toisen, paremmin mikroverkkojen simuloimiseen soveltuvan ohjelman käyttöä suositellaan, kuten MathWorks Simulink ohjelmaa.

ASIASANAT:

Mikroverkko, energiatehokkuus, hajautettu tuotanto

CONTENT

FIGURES

EQUATIONS

TABLES

LIST OF ABBREVIATIONS (OR) SYMBOLS

AC	Alternating current
BSS	Battery storage system
DC	Direct current
DER	Distributed energy resource
DES	Distributed energy system
DG	Distributed generation
ESS	Energy storage system
EV	Electric vehicle
HV	High voltage
LV	Low voltage
MG	Microgrid
MV	Medium voltage
PV	Photovoltaic
RES	Renewable energy resource
RMS	Root mean square
V2G	Vehicle to grid

1 INTRODUCTION

Under strickening restrictions and policies set by different levels of governance to mitigate climate change, numerous technological solutions are being studied and experimented to find more efficient, environmentally friendly, and sustainable ways for utilizing energy in the society. The conventional centralized energy distribution network consisting of inefficient fossil fuel based energy production plants utilizing finite and polluting fossil fuel resources are being gradually replaced around the world by renewable energy sources (RES). These include units such as photovoltaic (PV) panels, micro turbines and wind turbines paired with energy storage systems (ESS). RESs are considered as distributed generation (DG) and provide several advantages to the energy distribution network such as energy security, peak load reduction, reduction in grid losses, power quality support and reliability improvements. Adding to this, the use of RES as DG units entails economical, technical, and environmental benefits by cutting down carbon dioxide emissions and contributing to reducing nations carbon footprints. (Justo et al. 2013.)

However, integrating RESs to the mains grid also brings forth challenges. Due to the intermittent and unpredictable nature of RESs caused by various different factors such as weather conditions, the fluctuating power flow from RES results in problems, especially in the main grid (Planas et al. 2015). To tackle this, RESs are usually preferred to be paired up with ESSs, such as battery storages systems (BSS) to stabilize the balance of demand and supply. If a system like this is setup so that it can operate independently from the main grid, it is called a microgrid (MG). MGs are a self-sufficient distributed energy system (DES) including local DG units and ESS that can serve the energy demands of a certain area independently, for example in the case of a fault in the grid. (Dragičević & Blaabjerg 2017.)

Alternating current (AC) has been the prevalent technology used for transmitting electricity in the grid since the early 20th century when AC won the “War of the Currents” (Justo et al. 2013). However, direct current (DC) technology has recently become more popular for high voltage (HV) power transmission due to advantages such as higher power density, stability, and cost (Planas et al. 2015). Moreover, the increased development in power electronics as well as the constantly growing production of DC-based devices and appliances, such as electric vehicles, smart phones, power tools, computers, lighting etc. in the recent years have made DC distribution systems seem more promising. Thus, low voltage DC (LVDC) MGs have been and are being widely studied for their advantages regarding energy efficiency and reliability over LVAC systems. (Justo et al. 2013.)

This thesis is done for the New Energy research group of Turku University of Applied Sciences that is involved in a project called RESPONSE. RESPONSE project examines local and sustainable energy solutions implemented with the help of microgrids. A local microgrid and an associated energy management system will be designed and implemented in the project for Turku Student Village located in Turku, Finland. The local microgrid consists of solar PV plants, an energy storage, charging stations for electric vehicles (V2G), a heat pump and the electrical equipment of residential buildings, as well as an electrical network connecting these devices.

This thesis includes a literature review that intends to 1) cover the advantages and disadvantages of LVDC technology compared to LVAC technology in microgrids, and 2) 2) address the technological efficiency and the energy savings produced by LVDC technology compared to LVAC technology in microgrids. With the intention to validate the results from part two, a simulation is performed with DIgSilent PowerFactory 2020 simulation software by using the technical features of commercial solutions found on the market.

2 MICROGRIDS IN GENERAL

Unlike the centralized main grid where large power plants produce energy and distribute it over long distances, a MG is a self-sufficient intelligent energy system that provides energy locally at a certain geographical area and it is capable of operating independently or connected to the main grid (Planas et al. 2015; Wood 2020). The MG is not particularly a new invention, since they have been heavily utilized for decades in, for example aircrafts, spacecrafts, space stations, large ships, submarines, and datacenters. Due to the increase in RES installations worldwide, such as wind and solar energy, MGs have recently become an even more attractive solution. (Justo et al. 2013.)

The energy system of a MG consists of distributed energy resources (DER) such as wind turbines and solar photovoltaic (PV) panels, energy storage devices such as flywheels, supercapacitors, batteries, and loads. (Bevrani et al. 2017.) The advantage of microgrids is their ability to work in both islanded mode and grid connected mode for improved reliability and energy security. (Planas et al. 2015; Francés et al. 2018.) Moreover, intermittent and fluctuating renewable energy is utilized more efficiently inside the MG and are therefore more environmentally friendly than the conventional grid. Also, they allow net-zero-energy building if they consist of RESs (Planas et al. 2015).

2.1 Operation modes and control

Microgrids can be categorized into two main groups: grid-connected microgrids and stand-alone microgrids. The grid-connected microgrid can operate either in grid-connected mode or islanding mode. In the grid-connected mode the main grid acts as a backup energy source in a situation when the DERs connected to the MG cannot provide sufficient power. In a grid-connected MG the key control issue is efficient operation. When the main grid connection suffers from blackouts or becomes unstable, the MG is converted to the islanding mode and becomes self-sufficient. In islanding mode operation, the control of voltage and frequency become the main issue. The stand-alone, or off-grid MG is always operating in islanding mode without the connection to the main grid because it is usually installed in remote areas such as mountainous areas or islands without a power grid, or large ships. MGs can work in DC or AC mode, and in some cases even both. (Aboelsaud, Ibrahim & Garganeev 2019.)

2.2 DC and AC

In a DC electrical circuit, the current flows in one direction only, while in an AC circuit the current direction changes multiple times with a certain frequency. For DC the waveform is a straight line, whereas one cycle of AC can be illustrated with a waveform called AC sine wave (Figure 1). The effective value of AC voltage is always less than the peak value. The effective value, or root mean square (RMS) value of AC voltage, is equivalent to the DC voltage of the same value. (Fardo & Dale 2008.)

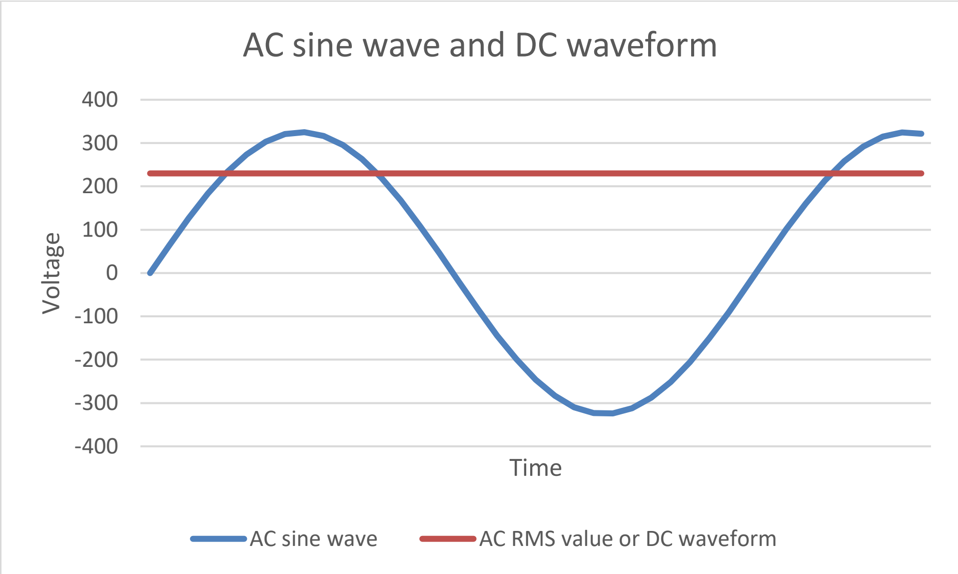

Figure 1. AC sine wave and DC waveform.

2.3 Power converters

DG units are energy generators, for example solar PV plants, tide, wave, wind and hydro turbines, and small combined heat and power (CHP) plants, that serve the energy needs of a local standalone system or the mains grid. Depending on the DG unit, they generate either DC or AC electricity. DG units cannot be directly connected to a grid since the characteristics of the produced energy do not match the specific requirements of the grid (Bevrani 2017). The desired voltage magnitude, frequency, and phase angle for connecting them to a grid or to consumers are obtained with specific converters and power electronic interfaces (Justo et al. 2013). Power converters consist of power semiconductor switches, diodes, inductors, capacitors, resistors, transformers, and a controller that regulates the power flow. The flow of power in a converter can be either uni- or bidirectional depending on the application. (Shahbazi & Khorsandi 2017.) In a stand-alone microgrid the power electronics supply all the loads in the grid, even the critical ones, and this requires that the converters are capable of supplying a constant voltage and frequency at any given time. In addition, a MG consisting of several different DG units and converters that supply same loads need to share the load equally which requires additional control. (Sharkh et al. 2014.) Power converters are classified according to whether the input and output is AC or DC (Figure 2).

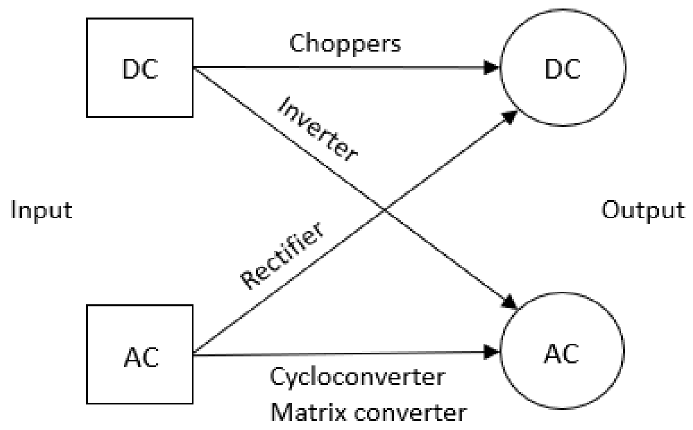

Figure 2. Different conversion types of converters.

DC-DC conversion

DC-DC converters, also known as choppers, take input voltage and current ratings of the DC power source and generate controlled DC voltages and currents in the output. The use of DC-DC converters is mainly limited to DC MGs. (Shahbazi & Khorsandi 2017.) For example, a solar PV system or a BSS can be linked to a DC bus with a buck-boost DC-DC converter. A buck-boost converter can reduce or increase the input DC voltage at the output. A buck-boost converter consists of two technologies: buck converter and boost converter. Buck refers to reducing the voltage and boost to increasing the voltage. (Sivakumar et al. 2016.)

DC-AC conversion

DC-AC converters are more commonly known as inverters. They are used to convert DC electricity into controlled and constant AC electricity suitable for the grid and its appliances. (Shahbazi & Khorsandi 2017.) Depending on the requirements of the system, the inverter can either have a single- or a three-phase output (Manandhar, Ukil & Kiat Jonathan 2015). For example, three-phase DC-AC inverters can be used to link DC MGs to the main AC grid to work in a grid-connected operation mode that allows bidirectional power flow (Shahbazi & Khorsandi 2017).

AC-DC conversion

AC-DC converters or rectifiers are basically inverters but with the components reversed. They convert AC electricity to DC with controllable voltage and can be used to connect AC-based electricity generating units to DC network (Justo et al. 2013). For example, a wind turbine generating AC electricity can be connected to a DC bus of a DC MG. AC-DC converters are also used for example to charge a battery with the AC grid.

AC-AC conversion

AC-AC converters transform AC to another form of AC with controllable phase, magnitude, and frequency. The most common method is to first transform AC to DC and then back to AC. (Shahbazi & Khorsandi 2017.) These kinds of AC-DC-AC converters can be used to for example connect a wind turbine to an AC grid.

2.4 Basic MG structure

In many cases, the basic MG network is assumed to be radial, and as mentioned earlier, consist of several different DERs, ESSs, as well as loads. The following figure illustrates a basic structure of a MG (Figure 3). The MG can be connected to the main grid at the point of common coupling (PCC) by a static switch (SS). The SS's main function is to disconnect the MG from the utility grid in the case of emergencies, for example when the main grid is experiencing faults and disturbance, or for maintenance purposes. In these cases, the MG would operate independently in islanding mode. Each DER has a power flow controller and a circuit breaker (CB) for disconnecting locally from the MG to avoid the effects of faults in the network. To control and monitor all the DERs, maximize efficiency, and to ensure network stability a microgrid central controller (MGCC) is required. MGCC operates as the head of the MG hierarchical control system, and the load controllers (LC) as well as the microsource controllers (MC) at the lower hierarchical control level communicate with the MGCC. (Bevrani 2017.)

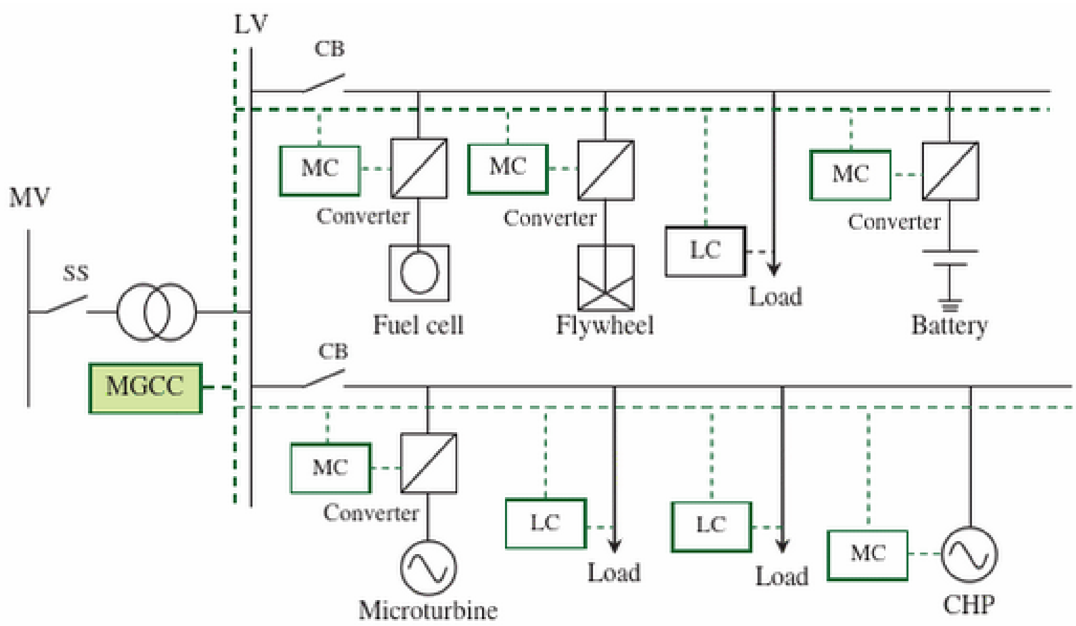

Figure 3. An example of a basic grid-connected MG structure with LV feeders and loads (Bevrani 2017).

3 LVAC AND LVDC MICROGRIDS

The mains electric grid operates on AC electricity and the grid can be divided into two systems: transmission and distribution system. The transmission system delivers power from power plants to the distribution substations while the distribution system delivers power from distribution substations to the consumers. (Justo et al. 2013.) For example, in Finland the transmission system transfers AC electricity in high voltage (HV) levels ranging from 110-400 kilovolts (kV), and the distribution system at medium to low voltage levels. Medium voltage (MV) level refers to 1-70 kV while low voltage (LV) refers to under 1 kV. (Energiateollisuus 2021.) In Finland, the normal voltage level at the consumer's end is usually 230/400 V and the frequency is 50 Hz (Fingrid 2021a; Fingrid 2021b). This thesis will concentrate on MGs connected to the grid at the LV level (under 1 kV).

MGs can be further divided into three groups: AC, DC, and hybrid MGs depending on the topology. In the most commonly utilized AC MG, all the electrical devices are connected together through an AC network, that can then be directly connected to the utility grid without the need of a power electric interface. A DC MG consists of DC-based devices, that are linked together through a DC-based network. DC MGs alone are uncommon, because a many electrical appliances utilize AC electricity, and thus, it is more likely that a MG has both, a DC and an AC bus, that are linked together inside the MG with a bidirectional inverter to combine the advantages of both systems. These kinds of MGs are called hybrid MGs. (Unamuno & Barrena 2015.)

3.1 LVAC MG advantages and disadvantages

In a LVAC MG the AC-based DG units, for example wind, hydro, tidal and wave turbines can be connected to an AC network, either directly or via AC-DC-AC power converters. The LVAC bus is then linked to the main grid via transformers. Also, the AC loads can be directly connected, but the DC loads require an AC-DC conversion stage for connecting to the LVAC system. DC-based DG units for example solar PV panels and fuel cells, as well as DC-based ESS units can be connected to the LVAC system via DC-AC inverters. (Justo et al. 2013.)

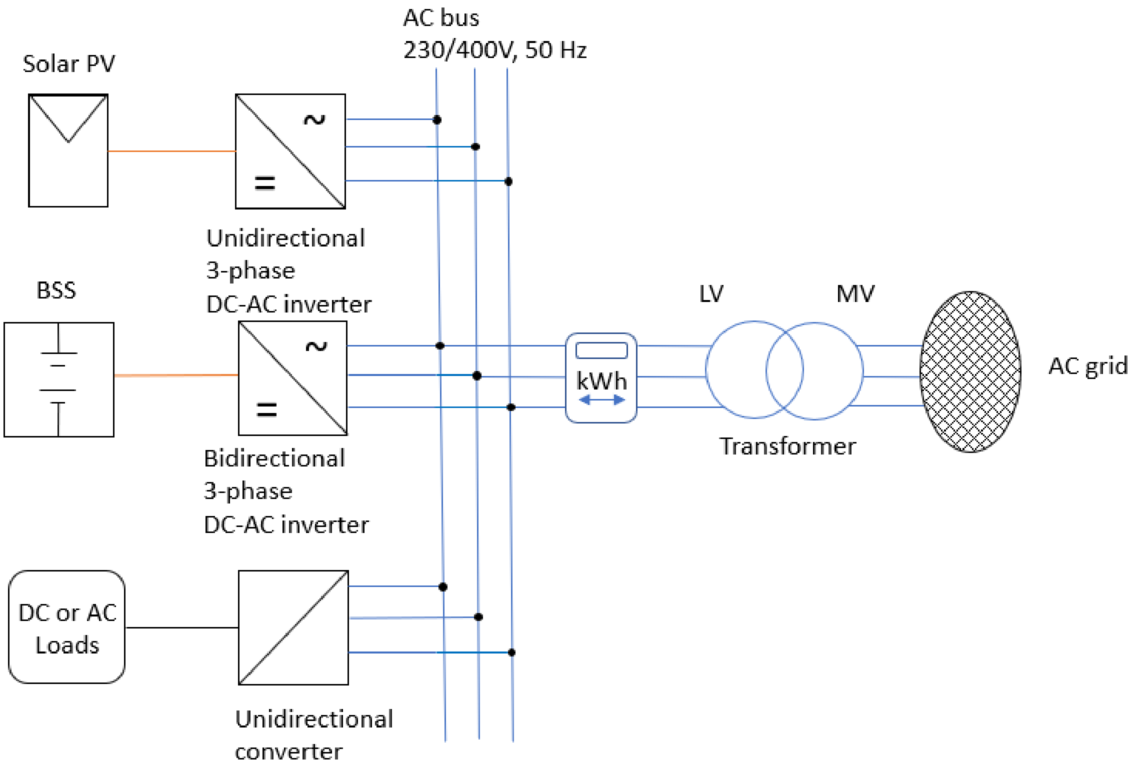

Figure 4. A simplified example of the conversion stages in a typical LVAC MG.

Because the LVAC MG is compatible with the existing AC power network, the existing AC infrastructure, protection techniques, standards and relevant engineering skills can also be directly applied. AC-based energy sources and loads can be, either directly connected to an AC common bus or via AC-DC-AC converter. (Semënov et al. 2017.) For AC-coupled systems it is not necessary to consider the compatibility of the voltages of the DC devices, because the inverters can operate at a wide DC-voltage range (Äijö 2019). However, AC systems consists of characteristics that need to be considered, such as reactive power, frequency, and phase angle. These features also make the AC system challenging to operate and control, and less efficient compared to DC systems. (Ali et al. 2012; Justo et al. 2013.)

3.2 LVDC MG advantages and disadvantages

LVDC MG is a LV distribution system where the DC based DG units, ESS units and loads can be directly connected to the DC network through a DC-DC converter. The AC based DG units require an AC-DC rectifier while the AC loads require an inverter for connecting to the LVDC MG. For grid connection, the LVDC MG requires a bidirectional DC-AC inverter to connect to the mains grid. (Justo et al. 2013.) A typical structure of a LVDC MG is presented in Figure 5.

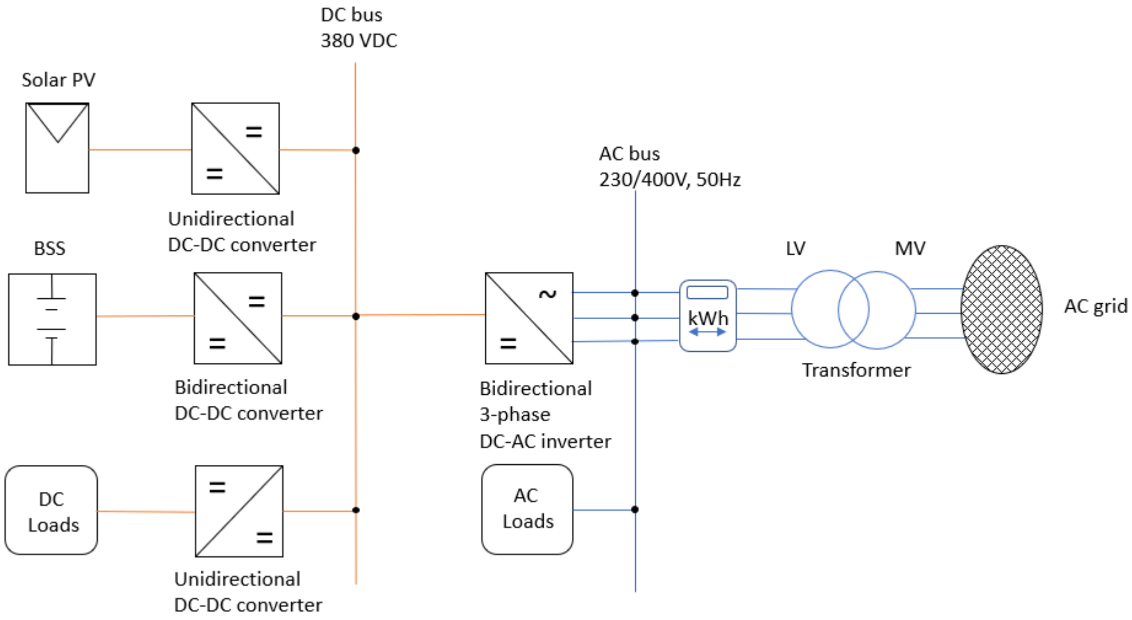

Figure 5. A simplified example of the conversion stages in a typical LVDC MG.

DC MG advantages are their high efficiency, simplicity, reliability, quality, and lower running costs. The high efficiency of DC MGs results from the reduction in conversion stages and the fact that DC system appliances do not have to be oversized like in AC systems due to the lack of reactive power and the requirements of the grid regarding reactive power. The integration of DC-based DG units, such as solar PV, to DC MG is easier compared to an AC MG. Since DC MGs only active power is transmitted in the lines, the DC MG power control is also very simple. In the absence of frequency and phase there is no need for frequency monitoring and synchronization of different sources in either islanding or grid-connected mode of a DC MG which results in a more reliable and stable system. In addition, eliminating conversion stages in DC systems decreases the number of points of failure and therefore increasing system reliability compared to an AC system. To ensure good power quality in AC systems, the control of four variables (frequency, voltage, phase, and power factor) is required. Whereas, in DC systems only the control of voltage level is required which results in better power quality. In addition to better efficiency and reliability, the reduction of conversion stages in DC systems also reduce the total cost of a DC MG system as well as the use of natural resources compared to an AC system. Since DC systems don't have reactive power, cable sizing and DC link capacitors is reduced, which in return reduces system costs even more. Also, the running costs of DC systems will be less than AC systems due to better efficiency. (Ali et al. 2012; Justo et al. 2013; Peyghami, Mokhtari & Blaabjerg 2017.)

The disadvantages of DC MGs compared AC MG systems are that they require a bulky rectifier at the PCC which affects DC MG's efficiency and reduces the edge that a DC MG has over the AC MG. In AC systems, transformers are a simple way to change voltage magnitude, but traditional AC transformers do not work with DC electricity (Donev et al. 2020). Thus, complex power electronic interfaces are required in DC systems for voltage regulation. Due to this, DC system are more complex regarding voltage step up and step down compared to AC systems, and even more so in the case that the voltages converted have a large difference between them. If an existing AC system is to be converted into a DC system, the investment cost for DC system would be more expensive, and this is mainly because the AC system already exists. For the AC system only some additional devices such as FACTS (Flexible alternating current transmission system) devices, control switchgear and communications need to be added, but for the DC system the transformer needs to be changed to a bidirectional DC-DC converter, and also some of the loads that do not work with DC electricity require change. (Ali et al. 2012.) The DC networks in general are more challenging compared to AC systems regarding protection systems and components. This is mainly because DC fault current does not have zero crossing like AC fault current, and thus the circuit breakers are more complex. Also, the lack of reactive impedance in DC cables presents challenges in fault finding. (Jovic & Ahmed 2015.)

In the future, LVDC distribution networks such as MGs are becoming ever more advantageous because of the increasing amounts of renewable DERs being integrated to the distribution networks, and the increasing amounts of DC loads emerging such as electric vehicles and mobile devices. (IEA 2021.)

3.3 Energy efficiency and savings of LVDC technology compared to LVAC technology in microgrids according to literature

DC distribution systems in buildings have been widely studied for energy efficiency reasons, and the results vary extensively. For example, implementing a grid connected DC MG into a building with solar PV, BSS and DC loads can have energy savings of approximately 10-12 % and at best approximately 18 % (Gerber et al. 2018). The savings differ because they depend on efficiencies of the power conversion devices used in the LVDC and LVAC systems, the DC bus voltage level, DC to AC load ratio, as well as the DC system topology.

3.3.1 Power electronics and power conversion

The conversion of electricity through any power electronic interface requires losses. These losses in converters result mainly from semiconductor switching losses, DC link capacitor losses as well as conduction losses. (Sharkh et al. 2014.) However, inverters (DC-AC) and rectifiers (AC-DC) are typically not as efficient as DC-DC converters. AC-DC converters can have up to 2,5 times more losses than a DC-DC boost converter (Gerber et al. 2021). For example, Ferroamp, a Swedish company specialized in power electronics for DC nanogrids provides an 8-kilowatt (kW) DC-DC converter with a maximum efficiency of 99,5 % for connecting a solar PV array to a DC network. For comparison, SMA, a popular German company specialized in power electronic interfaces for PV and battery systems provides a state-of-the-art 8 kW grid connected DC-AC inverter with a maximum efficiency of 98,3 % for connecting solar PV to an AC grid. (Ferroamp 2020a; SMA 2021a.) The efficiency of an inverter does not always correspond to the maximum efficiency. It varies depending on the maximum power point voltage (Vmpp) and the power output in relation to the rated power of the inverter (Figure 6). Nonetheless, the difference in efficiencies between these DC-DC converters and DC-AC inverters are not massive, but significant in the long run, especially in the case where several power electronic interfaces are connected to the same MG and the power loss results of the system are reviewed on an annual basis.

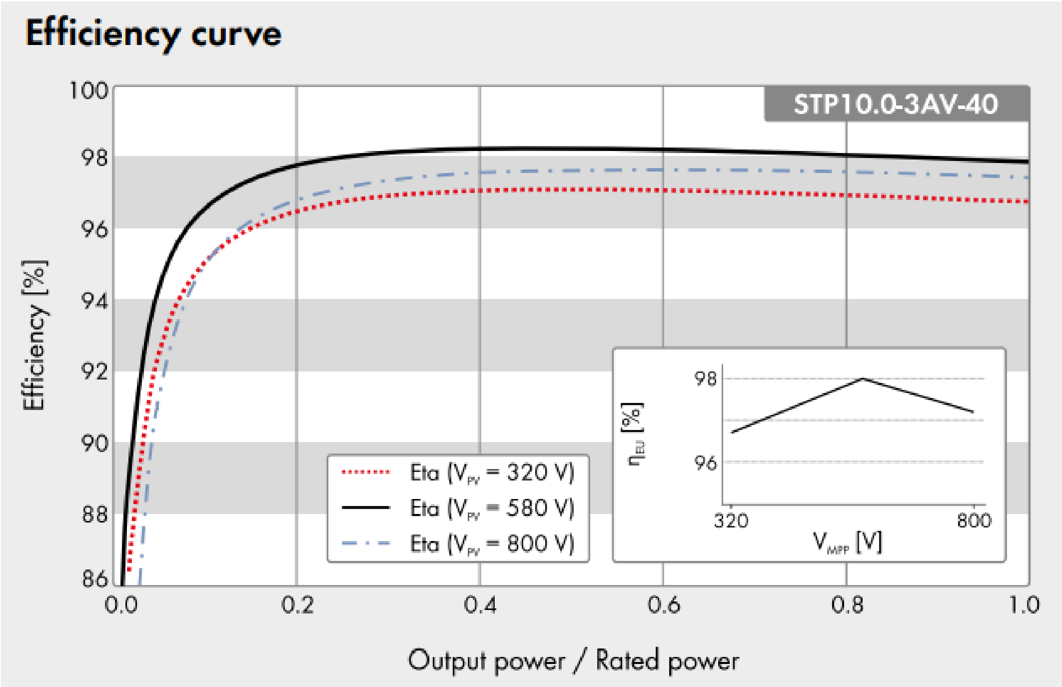

Figure 6. The manufacturer often provides a datasheet including the efficiency curve of an inverter. This is the efficiency curve of SMA Sunny Tripower 8 kW inverter (SMA 2021a).

Since DC energy sources and loads can be connected directly to a DC busbar, LVDC MGs require less DC-AC and AC-DC conversion stages than LVAC MGs, as can also be seen comparing Figure 4 to Figure 5. This can lead to 6 % lower power conversion losses in LVDC MGs compared to LVAC MGs (Manandhar et al. 2015). Also, DC MGs use generated solar PV energy 6-8 % more efficiently than traditional AC systems, partly because of the reduction in conversion devices, but also because of the reduction in the size of inverters for export PV energy as well as due to the improved efficiency of the battery system in a DC MG (Fregosi et al. 2015).

3.3.2 DC load ratio

However, whether the LVDC MG with DC based energy sources is actually more energy efficient than the LVAC MG, depends on the amount of DC loads there are connected to the system compared to AC loads. Provided that the DC load ratio exceeds a certain threshold, the DC distribution system is more efficient, otherwise the AC distribution system is the better option. As the DC ratio increases, the loss rate of the LVDC MG continues to decline, while in the LVAC MG it gradually increases. The explanation for this is that the more DC electricity, for example from solar PV production, is consumed on the LVDC side as the DC load ratio increases, the less electricity is transferred to the LVAC side through the bidirectional DC-AC inverter that has a lower efficiency compared to the DC-DC converter on the LVDC side. (HuipengLi et al. 2020.) For example, charging an EV on the LVDC side requires a DC-DC converter which is more efficient compared to the combination of the DC-AC inverter and the AC-DC rectifier that the solar PV electricity has to go through to charge an EV if it is connected to the LVAC side (Tan et al. 2016)

3.3.3 Bus voltage level

The cables in any electrical system are mainly dimensioned according to the current transferred through them, and the current depends on the system voltage and power level according to the power equation below, where *P* is electrical power (considers only active power), *U* is voltage (V), and *I* is current (A).

$$P = UI \qquad \text{(W)}$$

Equation 1. Electrical power equation (Mäkelä 2005).

The current transferred through the cable's conductor, insulation and outer sheath causes voltage drop and power loss in the cable's impedance in the form of heat. The greater the current loading on the cable, the more power loss is generated. Power loss in a DC cable conductor can be roughly calculated according to the equation below, where P_h is power loss (W), *I* is the current (A) and *R* is the resistance of the cable conductor per length (Ω/km or Ω/m). (Suomi 2010.)

$$P_h = I^2 \cdot R \qquad \text{(W/m)}$$

Equation 2. Power loss equation (Mäkelä 2005).

Thus, the higher the system voltage, the less current is required for the same amount of power, and therefore, less power loss through heat. Thus, the bus voltage level of an electrical system has a remarkable effect on the energy efficiency.

In order to minimize the complexity of the system and to ease the connectivity to the grid, it is typical that the bus voltage of a LVAC network is the same as the voltage of the LV grid which as mentioned before in Finland is 230/400 V. As mentioned before, the LVDC MG needs a power conversion interface for the connection to an AC grid, so the system is more complex anyway compared to a LVAC MG. However, this allows for the increase in voltage on the DC side for energy efficiency reasons. For example, increasing the DC bus voltage level to 400 VDC can offer up to a 10 % improvement in energy efficiency throughout the year compared to a conventional LVAC system (230 V RMS) in commercial applications (Anand & Fernandes 2010).

Increasing the bus voltage level on the DC side even more would have additional benefits. For example, the output voltage of a string of panels is determined by the number of panels connected in a string. Increasing the bus voltage to 760 V, or higher, instead of 230 V in a LVDC MG means that more solar PV panels could be connected in series. (Carlstedt 2014.) This would result in the utilization of fewer DC-DC converters and less current running through the cable, and therefore increase the energy efficiency of the system. Although, increasing the bus voltage level would increase the input and output voltage difference of the DC load converters, and this affects the efficiency of the DC-DC converter (Anand & Fernandes 2010). Therefore, the bus voltage level should be decided according to the voltage requirements of the DC loads connected to the system. In some cases, it might be beneficial to have several busbars with different voltage levels for the connection of DC load with different voltage requirements.

Higher bus voltage might also decrease the cost of the system, because smaller diameter cables would be sufficient, less converters and less cabling is required, and also fewer work hours for installing (Anand & Fernandes 2010; Carlstedt 2014). However, an analysis of the costs is outside the scope of this thesis.

3.3.4 Cables

Unlike DC electricity networks, AC networks have reactive power which causes more power loss in the system cables compared its DC counterpart. Due to the characteristics of AC electricity AC cables have inductance and capacitance which cause even more power losses (Justo et al. 2013.) Although, the power loss from inductance and capacitance in AC cables is more significant in HV distribution systems than LV. In addition, there is a relation between AC and DC cable resistances (Equation 3), which concludes that the resistance in AC cable is always higher than in DC cables (Elsayed, Mohamed & Mohammed 2015).

$$R_{ac} = \frac{\pi \cdot r^2}{\pi \cdot r^2 - \pi \cdot (r - \delta)^2} \cdot R_{cc}$$

Equation 3. Relation between AC and DC cable resistances (Cirino et al. 2009).

$$U = \frac{\hat{u}}{\sqrt{2}}$$

Equation 4. The relationship between RMS value and peak value (Mäkelä 2005).

Due to reactive power the cables in an AC system need to be larger in diameter, which increases the use of natural resources as well as costs. AC cables and lines also create electromagnetic interference that need to be considered for example when designing cable routes. (Justo et al. 2013.) AC cables also require relatively more insulation if comparing, for example 230 VAC RMS and 230 VDC. This is because the peak value of AC voltage is more than 40% higher than its RMS value (Equation 4). Insulation thickness in return affects the cost of cables.

4 RESPONSE-PROJECT

RESPONSE is a five-year project funded by the European Commission's Horizon 2020 Framework Programme, and it aims to find smart, energy positive and sustainable integrated solutions for neighbourhoods and cities. Turku University of Applied Sciences (TUAS) together with several other companies, both local and foreign, are planning and designing a LVDC nanogrid between two separate building blocks for Turku Student Village (TSV). The two blocks being referred to are Tyyssija and Block 5. Tyyssija is a new building that is under construction at the moment, but should be complete by the end of 2021, and Block 5 consists of four separate buildings (5A-5D) (TYS 2021). The location and site are illustrated more specifically in the picture below (Figure 7).

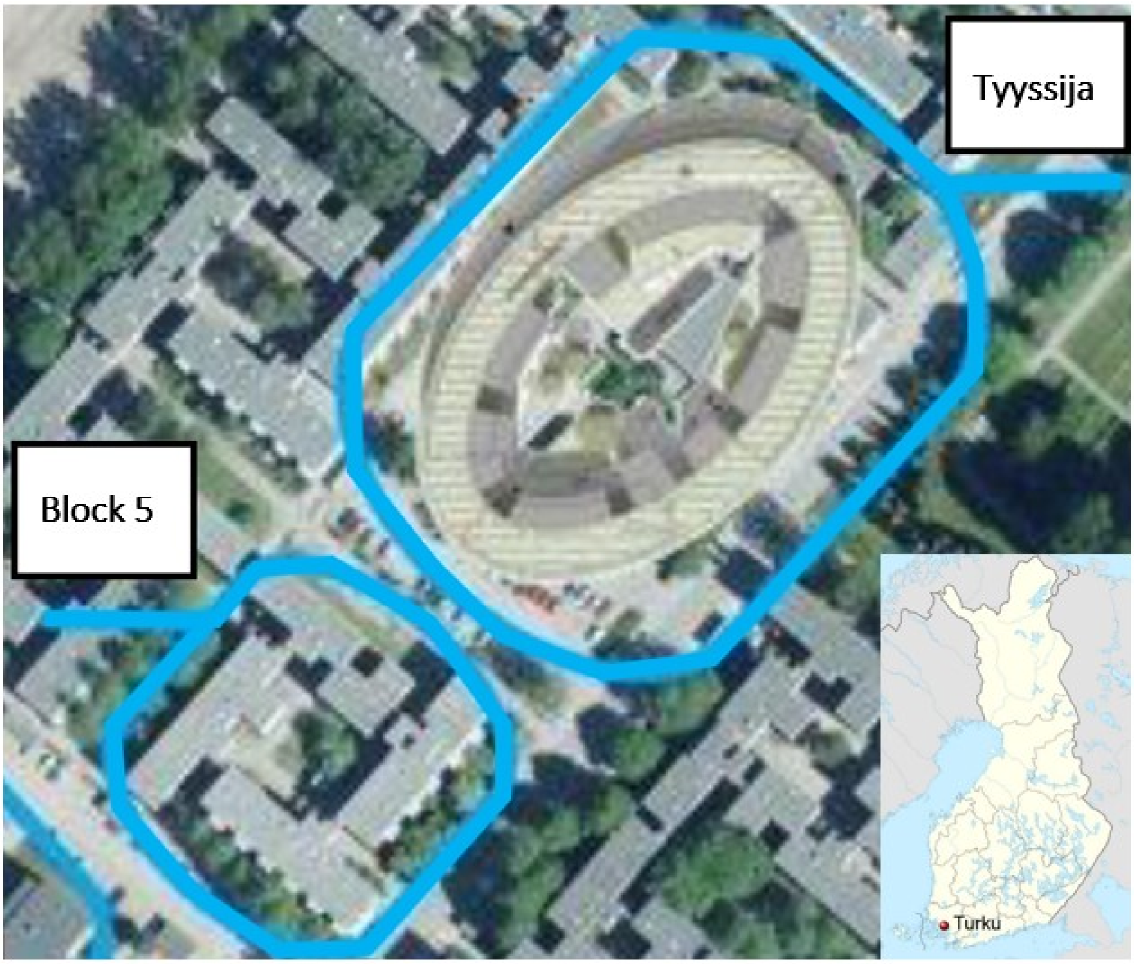

Figure 7. A map of the site where the microgrid is being implemented in TSV, Finland.

The electrical structure including the main components of the designed hybrid AC/DC grid for the RESPONSE-project (Figure 8) and the AC network of comparison (Figure 9) are illustrated in the diagrams below. The blue lines represent the AC part of the electrical system whereas the orange lines represent the DC network.

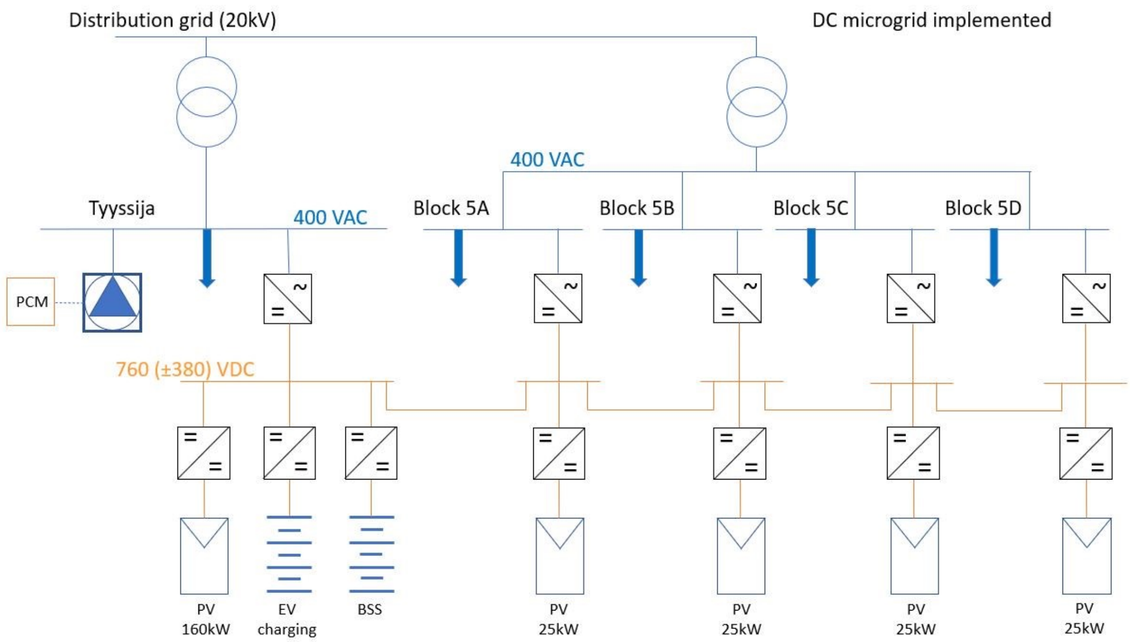

Figure 8. A simplified illustration of the planned hybrid network for the RESPONSE-project and for this simulation.

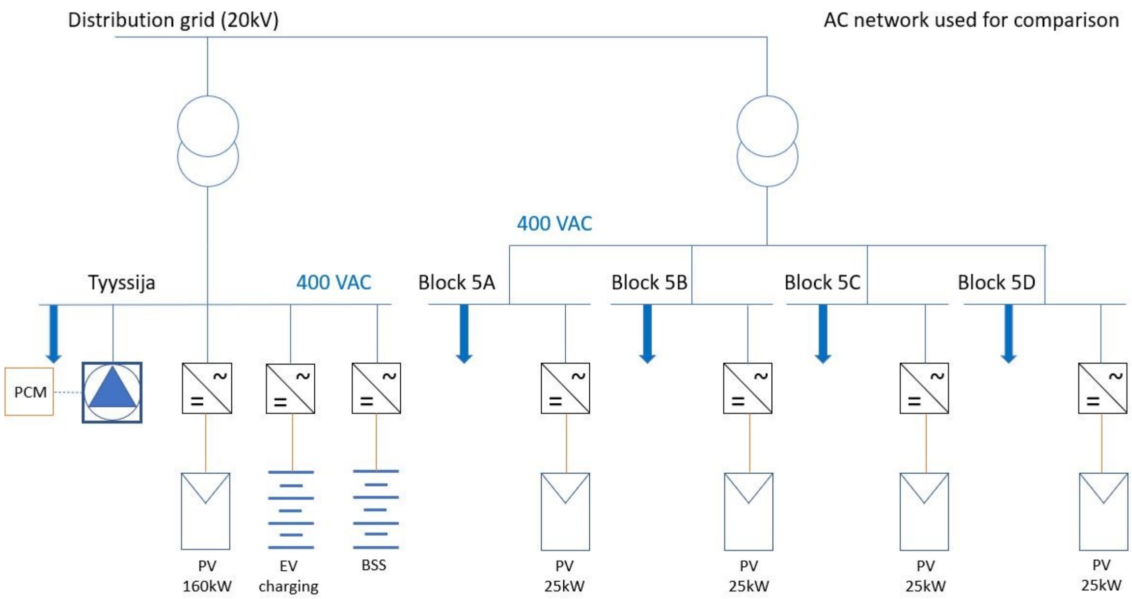

Figure 9. A simplified illustration of the AC network without the DC network.

5 SIMULATION

This simulation is done with the intention to validate the findings from literature mentioned in chapter 3.3 regarding the energy efficiency and energy savings of LVDC technology compared to LVAC technology in microgrids using a real-life example. The simulation models were created in DIgSILENT PowerFactory 2020, a software used for analysing generation, transmission, distribution and industrial systems of power systems, and the simulations were performed with the Quasi-Dynamic Simulation tool in PowerFactory 2020 (PowerFactory 2021). This tool calculates the power flow and power loss results for every hour of the year and allows to gather relevant data from the simulation afterwards. The power losses from cables, power conversion and transformers were considered to calculate and compare the energy efficiency and energy savings.

Parts of the simulations had to be manually calculated using Microsoft Excel, because PowerFactory 2020 does not allow to simulate a hybrid AC/DC grid, it does not provide power loss calculation results when simulating a DC network, and the inverter efficiencies could not be adjusted in the required Active Input Mode. This led to the simplification of the simulation models.

The simulation parameters were set according to the technical features of commercial solutions found on the market and the data available for the project and are described more thoroughly in the Materials and methods -section.

5.1 Materials and methods

5.1.1 Loads

For this simulation only the residential loads were considered. The planned heating, ventilation, air-conditioning (HVAC), phase change materials (PCM), as well as electric vehicle (EV) charging points for the site were left out for simplification. The residential loads are connected to the AC side in both cases (blue arrows). All the individual household loads in one building are considered as one big load for that specific building. Therefore, Tyyssija’s loads are considered as one load and the separate four buildings (5A-5D) of Block 5 are demonstrated as separate loads. The information for the number of apartments for Tyyssija and the peak load for Block 5 was available. Typical annual load profiles for different kinds of apartments and houses were used for estimating a load profile for Tyyssija (Mutanen, Lummi & Järventausta 2019). Measured data was available for Block 5, and an hourly load profile for one year was constructed for each building (5A-5D). The main results of the calculations, as well as the more detailed hourly load profile can be seen below,

Table 1. The different apartments in Tyyssija building as well as the peak power and total annual consumption of the whole building.

Tyyssija		
Studio apartments	162	
1-bedroom apartments	24	
Total	186	
Peak power	71	kW
Consumption	303	MWh/a

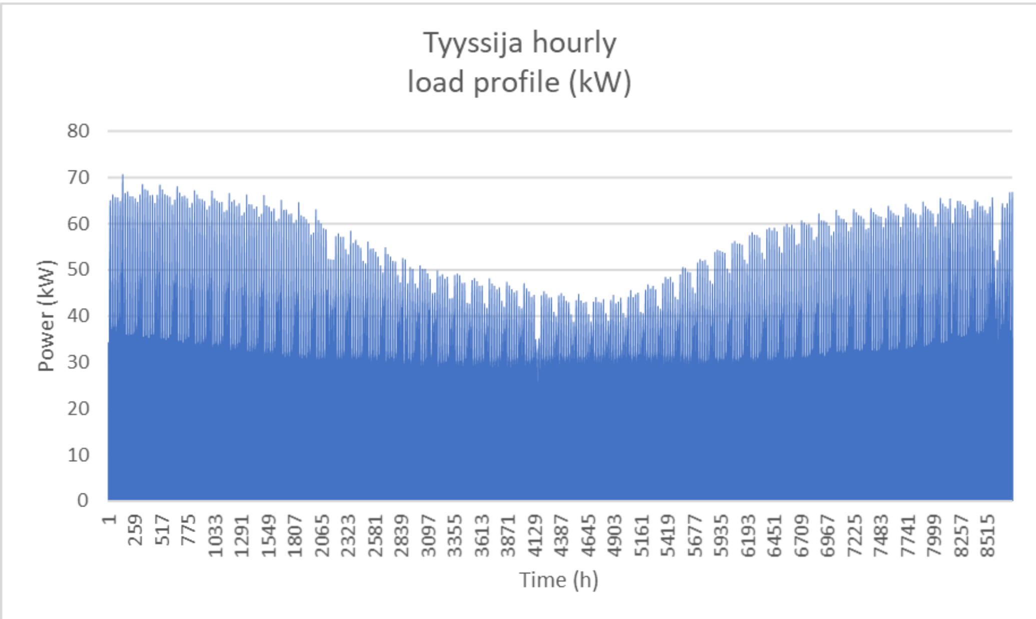

Figure 10. The hourly load profile used for Tyyssija building.

Table 2. The total peak power for the four buildings in Block 5 together (5A-D) and their total annual consumption.

Block 5 (5A-D)		
Peak power	60	kW
Consumption	268	MWh/a

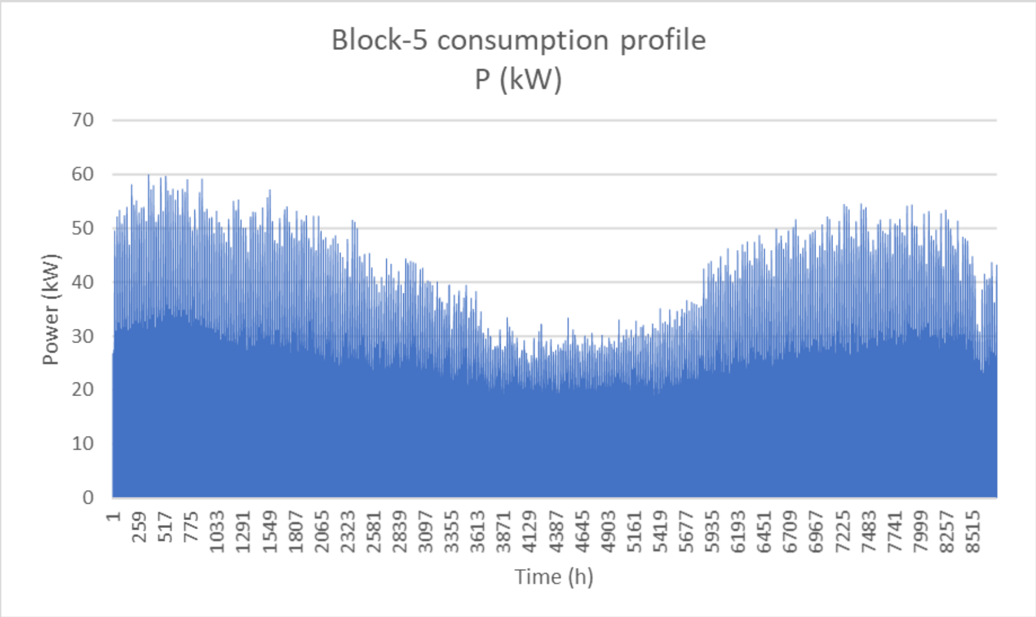

Figure 11. The hourly load profile for the Block 5 buildings (5A-5D).

5.1.2 Solar PV

Solar panels are installed for this project for local generation. One PV plant is installed on the roof of Tyyssija facing south and the other four on the roofs of the four separate buildings in Block 5 (A-D) also facing south. The peak power of the solar PV arrays installed can be seen in the table below (Table 3).

Table 3. The total solar PV peak power installed for both, Tyyssija and Block 5.

Solar PV peak power		
Tyyssija	160	kWp
Block 5 (5A-D)	100	kWp

Solar PV production is dependent on solar irradiance which varies significantly throughout the year due to numerous variables including location, seasonal and weather variations, ambient temperature, orientation, inclination, shading etc. (Mertens 2014). These variables make accurate calculation of produced electricity from solar PV challenging. Thus, a free online solar irradiation tool called PVGIS interface developed by European Commission Joint Research Centre was used for this simulation to calculate the amount of hourly PV power for a time period of one calendar year (PVGIS 2019). Other parameters for the calculations can be seen in the table below (Table 4).

Table 4. Parameters for PVGIS interface.

Parameters for PVGIS		
Simulated year	2015	
Coordinates	60.462	lat.
	22.288	long.
Elevation	36	m
Radiation database	PVGIS-SARAH	
Slope	44	deg.
Azimuth	0	deg.
System losses	0	%

The average hourly data gathered from PVGIS-tool can be seen from the graphs below (Figure 12 and Figure 13).

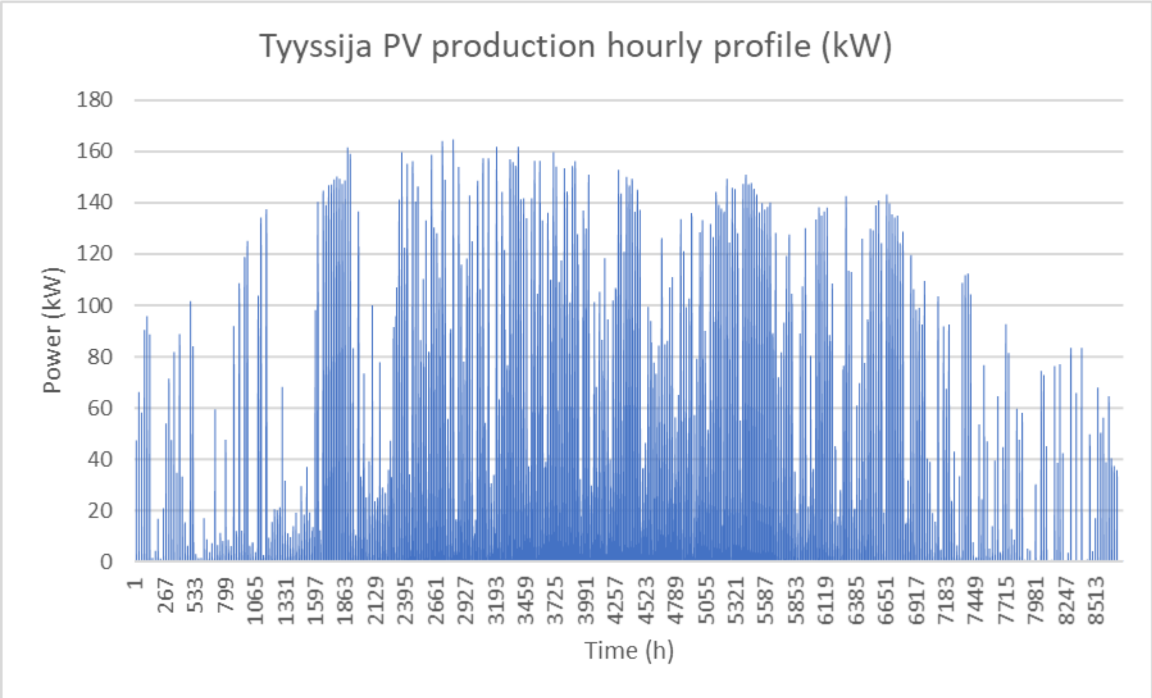

Figure 12. Solar PV production hourly profile used for Tyyssija (160 kWp).

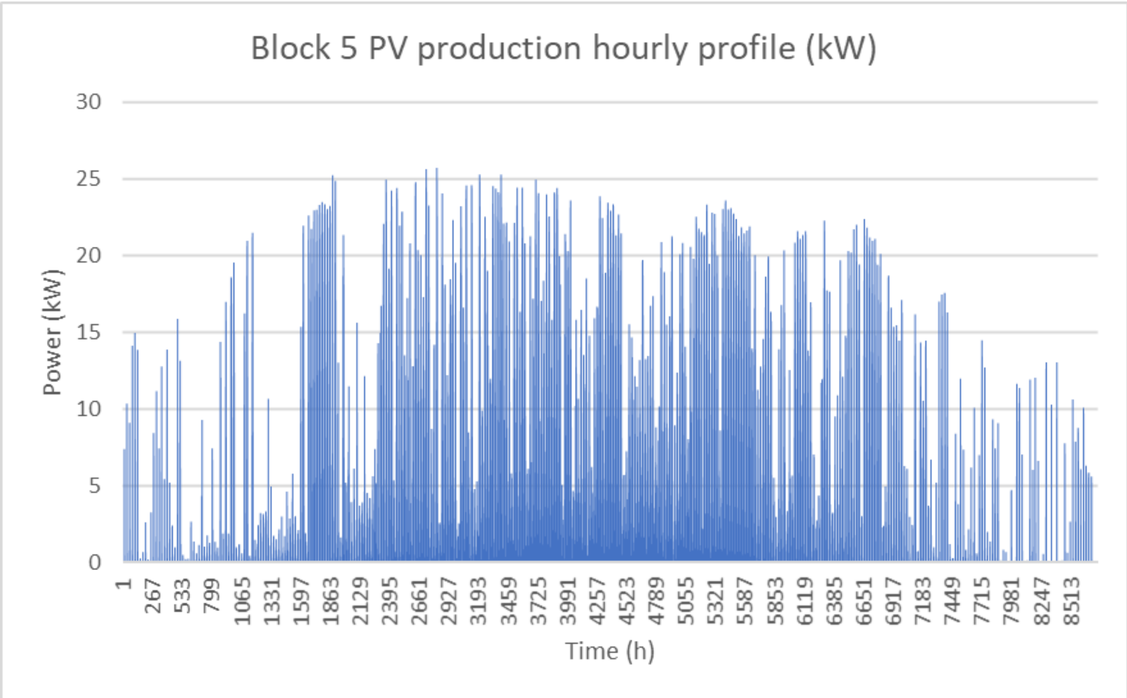

Figure 13. Solar PV production hourly profile used for each individual building in Block 5 (25 kWp).

5.1.3 Battery energy storage (BSS)

The BSS designed for this project was simulated only for the LVDC network on the LVDC side at Tyyssija. The BSS was not to the LVAC network, due to customer's request. More specifications of the BSS are listed in the table below (Table 5).

Table 5. Battery storage specifications.

Battery storage system		
Manufacturer	ELCON	
Energy capacity	50	kWh
Power	50	kWh

BSS is an important and inevitable component for the self-sufficiency of MGs. As in the traditional electricity grid, a MG must also always have an equilibrium of supply and demand. However, as mentioned before, renewable DERs, such as solar and wind, produce energy intermittently, and therefore the production and consumption of electricity do not correspond at all times. Therefore, ESS, such as BSS are essential, because they store the excess energy from renewable DERs at times when electricity production is greater than consumption, so it can be exploited at a time when the consumption is greater than production rather than being wasted. (Justo et al. 2013.)

5.1.4 Power converters

Converters used for this simulation are divided into two main groups depending on the cases compared: LVAC or LVDC. In both cases, Tyyssija's solar PV power output on the AC side was limited to 140 kW and the solar PV power output of each building in Block 5 were limited to 25 kW on the AC side. This was done according to existing plans of the project and to make both simulation models as comparable as possible.

Even though the efficiency curves for the inverters in the LVAC system were available, the efficiency curves for the inverters and converters in the LVDC system were not, so only the maximum efficiency values were used to calculate the efficiency losses in both cases to get as comparable results as possible.

LVAC Tyyssija

For the connection of the solar panels to the traditional LVAC grid, seven 20 kW unidirectional inverters are required at Tyyssija for the equivalent solar PV output (140 kW) as in the planned LVDC grid. SMA Technology's inverter's technical specifications for a 20 kW inverter were chosen to represent the simulated inverter. The relevant details were gathered from the manufacturer's datasheet and can be seen in the table and graph below (Table 6).

Table 6. Technical specifications of the inverter chosen for the solar PV in the LVAC system of Tyyssija (SMA 2021b).

SMA Sunny Tripower 20000TL		
AC output power	20	kW
Rated AC voltage	230/400	V
MPPT voltage range / rated input voltage	320-800 / 600	V
DC rated power	20440	W
Max efficiency	98,4	%

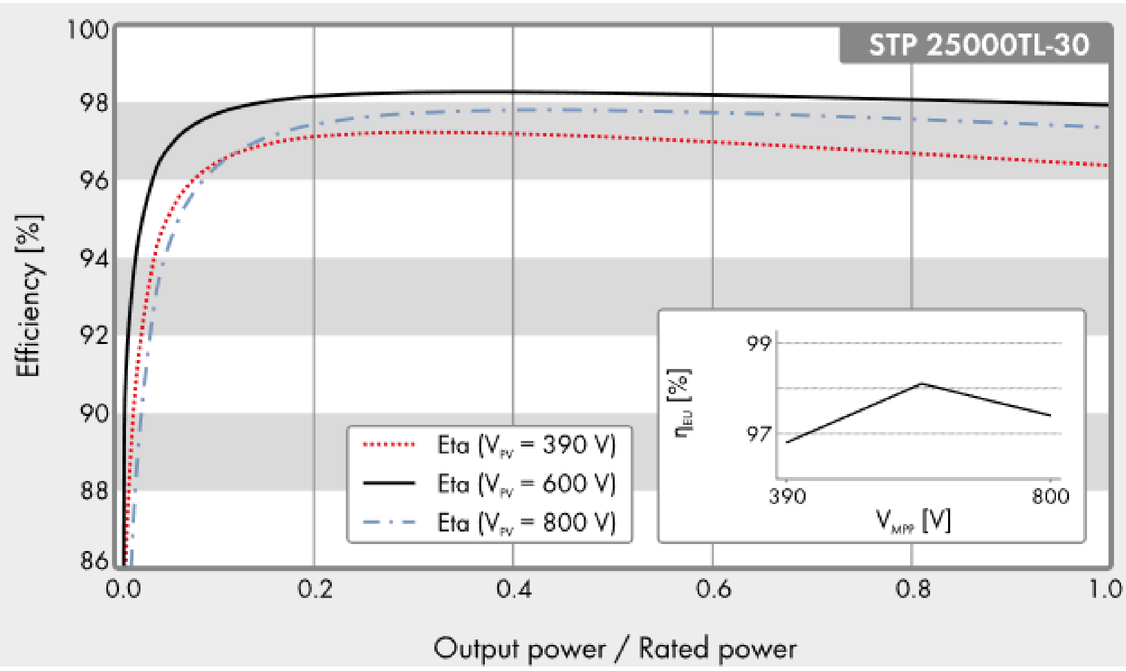

Figure 14. Efficiency curve of SMA Sunny Tripower 25000TL inverter which was on the same datasheet as the 20000TL inverter (SMA 2021b).

LVDC Tyyssija

The solar panels as well as the BSS are connected to the Tyyssija's main DC busbar via DC-DC converters. The solar panels are connected with 20 unidirectional 8 kW DC-DC converters (SSO) by Ferroamp and the BSS with nine 6 kW paralleled bidirectional DC-DC converters (ESO) by Ferroamp. The technical details can be seen from the tables below (Table 7 and 8).

Table 7. Technical data of the Ferroamp SSO (Ferroamp 2021a).

Ferroamp Solar String Optimizer (SSO)		
Output power	8	kW
MPPT voltage range	100-720	V
Output voltage range / nominal DC voltage	740-780 / 760	V
Max efficiency	99,5	%

Table 8. Technical specifications of the Ferroamp bidirectional ESO (Ferroamp 2021b).

Ferroamp Energy Storage Optimizer (ESO)		
Output power	54	kW
Output voltage range / nominal DC voltage	740-780 / 760	V
Max efficiency	99	%

According to the electrical planning, the main LVDC busbar is connected to the AC busbar with five 28 kW modular bidirectional inverters from Ferroamp (Table 9.)

Table 9. Technical data of the bidirectional inverter for the connection of the Tyyssija LVDC busbar to the AC busbar (Ferroamp 2021c).

Ferroamp EnergyHub XL (rack)		
Power	28	kW
Rated AC voltage	230 / 400	V
Nominal DC voltage	±380	V
Max efficiency		
DC-AC	98,5	%
AC-DC	98	%

LVAC Block 5

For the connection of the solar panels to the traditional LVAC grid, a unidirectional inverter is required. SMA Technology’s 25 kW Sunny Tripower 25000TL inverters were chosen for each one of the four buildings in Block 5 (5A-D) as for Tyyssija (Table 10).

Table 10. Inverters chosen for the connection of solar PV from each building of the Block 5 to the LVAC side (SMA 2021b).

SMA Sunny Tripower 25000TL		
AC output power	25	kW
Rated AC voltage	230/400	V
MPPT voltage range / rated input voltage	390-800 / 600	V
DC rated power	25550	W
Max efficiency	98,3	%

LVDC Block 5

The solar panels are connected to the LVDC network of each individual building (5A-D) with three 8 kW Ferroamp SSOs. For more specific details, see table 7 above.

According to the electrical design, the LVDC buses from each building (5A-D) are connected to the AC bus with a 28 kW Ferroamp EnergyHub Wall XL bidirectional inverter (Table 10).

Table 11. Technical specifications of Ferroamp's EnergyHub Wall XL (Ferroamp 2021d).

Ferroamp EnergyHub Wall XL		
Power	28	kW
Rated AC voltage	230 / 400	V
Nominal DC voltage	±380	V
Max efficiency		
DC-AC	98,5	%
AC-DC	98	%

Like mentioned earlier the efficiency curves for the inverter and converter in the LVDC system were not available, so just the maximum efficiency values were used.

5.1.5 Cables and other electrical devices

Cable layout, dimensions, and other technical data for the LVAC side of the system were provided for the project, but the lengths of the cables were estimated using an online map service for the city of Turku (Turun karttapalvelu 2021). This cable data was also used for the LVAC simulation parameters (Table 12). However, the data for the cable in the LVDC system connecting Tyyssija and Block 5 was not provided, and therefore needed to be roughly dimensioned for the simulation. The cable is assumably aluminium and it was dimensioned so that, in the case that the main grid gets disconnected from Tyyssija's side, it should be capable of transferring the whole PV production from Tyyssija to Block 5 (160 kW).

Table 12. Cable types and lengths used for the LVAC simulation.

Connection	Cable type	Length (m)
9671 New Trafo - Tyyssija SB	5x AXMK 4x185	80
9671 Old Trafo - DB1	2x AMCMK 4x300+88	80
DB1 - DB2	2x AMCMK 4x300+88	125
DB2 - Block 5C SB	1x AMCMK 4x150+41	50
DB2 - Block 5D SB	1x AMCMK 4x150+41	30
5D - 5A	1x AMCMK 4x150+41	30
5A - 5B	1x AMCMK 4x150+41	30
DB = Distribution board, SB = Switchboard		

The required cable area (mm^2) for the cable was calculated by using the electrical power equation (Equation 1), Ohm's law (Equation 5) and by calculating the electrical resistance of the conductor in terms of resistivity (Equation 6).

$$U = RI$$

Equation 4. Ohm's law (Mäkelä 2005).

$$R = \rho \frac{l}{A}$$

Equation 5. Electrical resistance equation (Mäkelä 2005).

Table 13. Parameters used for dimensioning the cable for the connection of Tyyssija to Block 5 and the relevant specifications of the cable.

Tyyssija – Block 5 cable		
Length (l)	200	m
Max power (P)	160 000	W
Voltage (U)	760	VDC
Current (I)	210,5	A
Specific resistance of aluminium (ρ)	27,2	10^(−9) Ωm
Allowed voltage drop	4	%

As a result, a cable with an area of 75,3 mm^2 would be sufficient, so the AMCMK 0,6/1 kV 3x95/29 aluminium cable from the Prysmian Group's cable catalogue was chosen for the connection of Tyyssija to Block 5 DC busbars (Prysmian Group 2018).

The DC cables from the solar panels to the inverters are not considered in these simulations because they are the same in both cases, and as a result the difference in power loss would be nonexistent. The cables connecting the BSS to the DC busbar via DC-DC converter are also not considered in these simulations because they are relatively short presuming they are to be located close to the DC busbar for energy efficiency reasons, and therefore account for an insignificant part of the power losses overall.

5.1.6 Transformers

Two 630 kVA transformers are simulated to both systems accordingly to the electrical circuit diagram of the site of the site. They are located at the far end of Tyyssija and connect the systems from the LVAC side to the 20 kV MVAC network. Other technical information about the transformers was not available, and therefore two 0,63 MVA 20/0,4 kV 1,29 GEAFOL transformers were chosen for the simulations from the PowerFactory 2020 Global library.

5.2 Simulated AC system

The LVAC network of comparison was successfully simulated on PowerFactory 2020 using the cable plan of the existing network at the area and the components found in the

PowerFactory 2020 library. The parameters were implemented for the corresponding components, and the solar PV and load profiles were added to the load flow section as time characteristics to the PV system elements and the load elements, respectively. The PV production profile gathered from PVGIS used as a time characteristic could only be added to the PV system element in Active Input Mode, and so the efficiency of the inverter integrated to the component could not be adjusted to correspond the specifications of the chosen inverter for the LVAC system, and so the efficiency losses of the inverter for the LVAC model had to be considered before adding the time characteristic to the LVAC PV system. The inverter efficiency losses were calculated in Excel. After this correction had been made, the power flow and power loss calculations were carried out using the QDS tool, and the relevant power loss results, including cable and transformer losses results were gathered from the simulation to form the final power loss result.

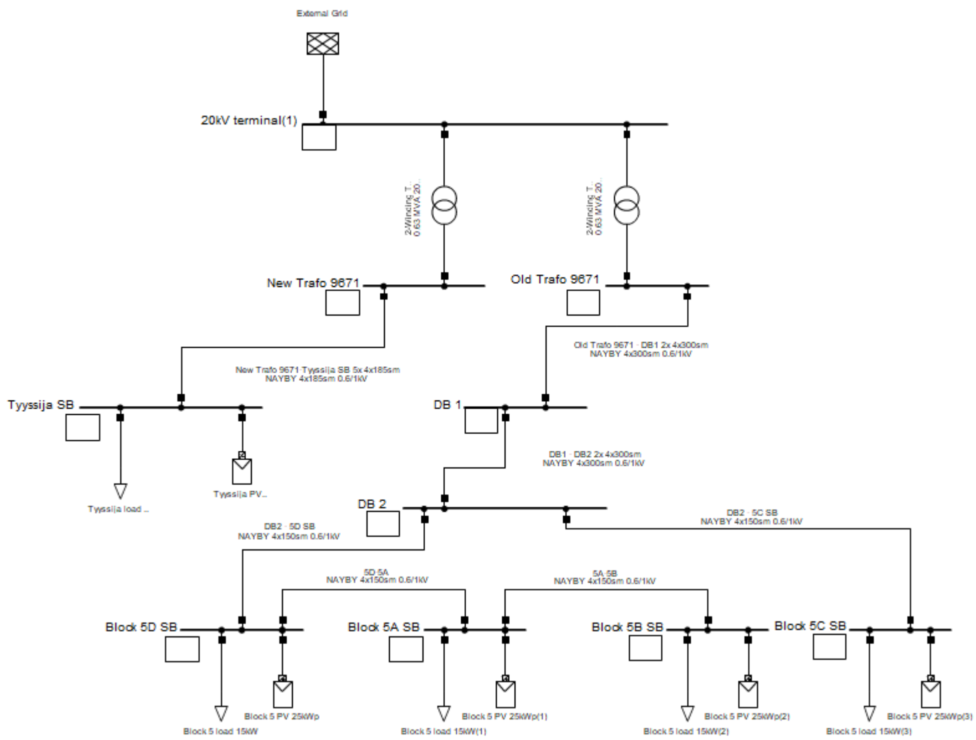

Figure 15. LVAC model simulated in PowerFactory 2020.

5.3 Simulated DC system

As mentioned earlier, Excel was used to calculate the power flow and power losses on the LVDC side of the AC/DC hybrid network (Figure 16). The logic implemented in the Excel calculations was as follows,

- Tyyssija solar PV and Block 5 solar PV production primarily supply the loads in Tyyssija and Block 5, respectively.
- If either building, Tyyssija or Block 5, has PV overproduction and the other does not, the required or available surplus solar electricity is primarily transferred to the loads of the other.
- Secondarily, the surplus solar electricity is directed to charge the BSS according to these conditions
    a. the BSS is charged primarily with the overproduction of Tyyssija and
    b. secondarily with the overproduction of Block 5.
- If there is still surplus solar electricity available, it is directed to the main grid and considered as export electricity.
- The BSS is discharged if needed
    a. primarily to supply the loads in Tyyssija, and
    b. secondarily to supply the loads in Block 5.

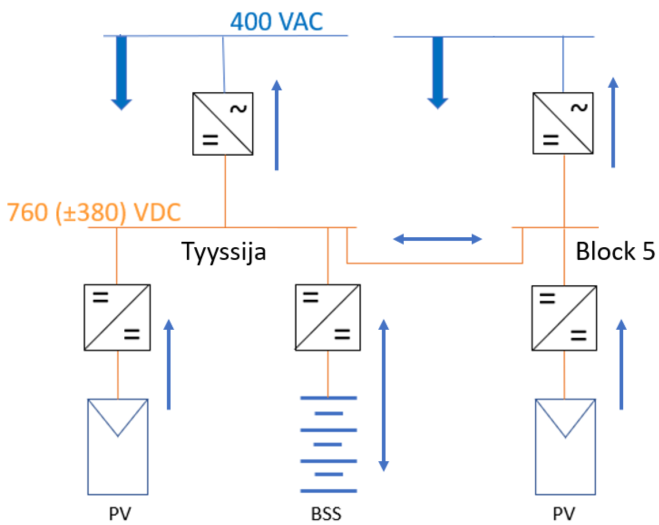

Figure 16. The LVDC part of the simulation was calculated manually with Excel.

The efficiency losses of the DC-DC converters, inverters, as well as the losses from the cable between Tyyssija and Block 5 were considered in the Excel calculations. Depending on the direction of the power flow per hour, the power transferred was multiplied by the efficiencies of the corresponding converter or inverter. After this the total power flow in the cable between Tyyssija and Block 5 was known and the power loss in the cable could be determined by using the power loss equation (Equation 2). After the power flow and loss calculations of the LVDC side were completed in Excel, the resulting import-export profile was conducted for both, Tyyssija and Block 5, was then implemented to PowerFactory 2020 for the simulation of the LVAC side of the hybrid AC/DC grid using the Quasi-Dynamic Simulation (Figure 15).

When the LVAC side of the hybrid grid was simulated, the power loss results, including LVAC cable and transformer losses, of both LVDC and LVAC side were then extracted out of the simulations and added together to form the final power loss result.

6 SIMULATION RESULTS

The simulation results show that the hybrid LVDC/LVAC network generates slightly more power losses than the traditional LVAC system (Table 14 and 15). The slightly higher losses seem to derive from the efficiency losses of the converters and inverters. This can be explained by the fact, that the electricity in the simulated hybrid LVDC/LVAC system is transferred through more power electronic stages to get to the loads, BSS or when exported to the grid, than in the simulated LVAC system.

Table 14. LVAC system simulation results.

LVAC system		**MWh/a**	**%**
Tyyssija	PV production	170,86	61,54 %
	Consumption	303,00	54,32 %
	Cable losses	0,26	0,87 %
	Transformer losses	11,56	38,85 %
	Inverter losses	3,71	12,48 %
	Sub-total of losses	15,53	52,20 %
Block-5	PV production	106,79	38,46 %
	Consumption	254,83	45,68 %
	Cable losses	0,95	3,21 %
	Transformer losses	11,45	38,49 %
	Inverter losses	1,82	6,11 %
	Sub-total of losses	14,22	47,80 %
Total	PV production	277,65	100 %
	Consumption	557,83	100 %
	Grid feed-in of total PV production	137,47	49,51 %
	Consumption from grid	447,39	80,20 %
	Total energy transfer in the system	725,04	100 %
	Total losses	29,75	4,10 %
	Self-consumption	140,18	50,49 %
	Self-sufficiency	140,18	25,13 %

Table 15. Hybrid LVDC/LVAC simulation results.

LVDC/LVAC system		**MWh/a**	**%**
Tyyssija	PV production	170,86	61,54 %
	Consumption	303,00	54,32 %
	Cable losses	0,25	0,83 %
	Transformer losses	11,55	38,57 %
	EnergyHub inverter losses	2,36	7,87 %
	SSO losses	0,85	2,85 %
	ESO losses	0,32	1,07 %
	Sub-total of losses	15,33	51,19 %
Block-5	PV production	106,79	38,46 %
	Consumption	254,83	45,68 %
	Cable losses	0,95	3,17 %
	Transformer losses	11,45	38,24 %
	EnergyHub inverter losses	1,56	5,21 %
	SSO losses	0,53	1,78 %
	ESO losses	0,12	0,39 %
	Sub-total of losses	14,61	48,78 %
Tyyssija <=> Block 5	Energy transfer	6,17	4,06 %
	DC cable losses	0,01	0,03 %
Total	PV production	277,65	100 %
	Consumption	557,83	100 %
	Grid feed-in of total PV production	125,62	45,24 %
	Consumption from grid	436,06	78,17 %
	Total energy transfer in the system	713,71	100 %
	Energy to storage from PV production	12,60	4,54 %
	LVDC side losses	5,75	19,20 %
	LVAC side losses	24,20	80,80 %
	Total losses	29,95	4,20 %
	Self-consumption	152,03	54,76 %
	Self-consumption w/o BSS	137,50	50,48 %
	Self-sufficiency	152,03	27,25 %
	Self-sufficiency w/o BSS	139,43	24,99 %

As can be seen from the results, the distribution of the total losses in both cases are the same, and the transformer losses account for most of the losses (Figure 17).

Even though the power losses are higher in the hybrid LVDC/LVAC system than in the LVAC system, the solar PV self-consumption of the hybrid system improved by over 4 % and self-sufficiency improved by over 2 % compared to the traditional LVAC system. This is mainly the result of the implementation of the BSS that intelligently stores part of the surplus solar PV electricity in the hybrid LVDC/LVAC system to supply the loads later when there is more demand than supply, rather than it being wasted directly to the grid. The benefit of the BSS can be verified by comparing the results of the hybrid LVDC/LVAC system without a BSS to the traditional LVAC system: without the BSS the self-consumption rate and its self-sufficiency rate are almost the same.

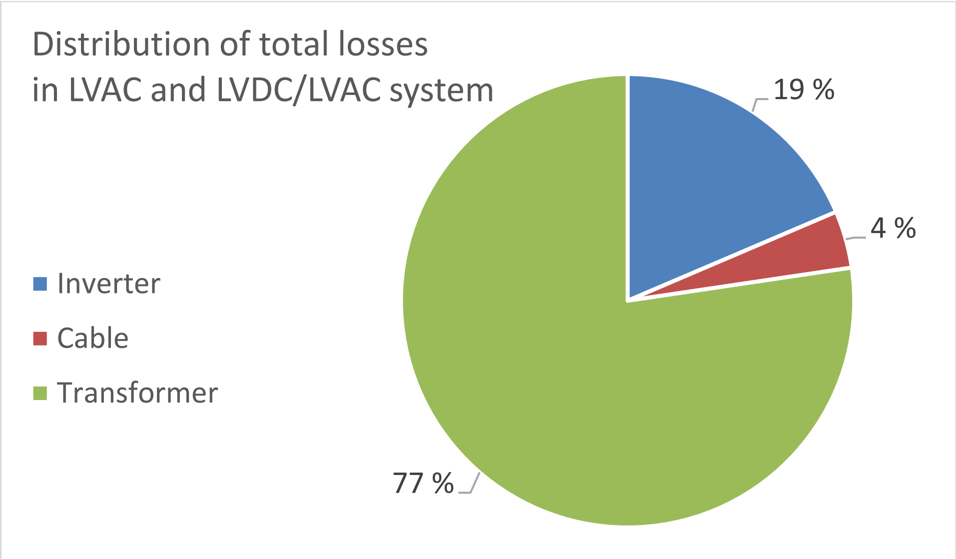

Figure 17. Distribution of total losses in LVAC and LVDC/LVAC system.

7 DISCUSSION

The objective of this thesis was to discuss the advantages and disadvantages of LVDC technology compared to LVAC technology in microgrids and address the technological efficiency and the energy savings produced by LVDC technology compared to LVAC technology according to literature. With the intention to validate the findings regarding the technological efficiency and the energy savings of LVDC technology compared to LVAC technology in microgrids, this thesis also included a simulation of a real-life case that utilized the technical features of commercial solutions found on the market.

This thesis concludes that LVDC technology has significant advantages compared to LVAC technology in regard to energy and resource efficiency, control, and cost-effectiveness. However, the disadvantages of LVDC technology are the complexity of voltage regulation and connection to the grid, as well as the utilization of traditional protection components compared to LVAC technology. The results from literature also indicate that the energy savings regarding a grid connected DC MG that is implemented into a building with solar PV, BSS, and DC loads are at least 6 % and at best 18 % compared to LVAC MG (Manandhar, Ukil & Kiat Jonathan 2015; Fregosi et al. 2015; Gerber et al. 2018). However, the results from the simulations conducted for this thesis show that the energy savings of the simulated hybrid LVDC/LVAC system were in fact 0,7 % less compared to the simulated LVAC system. Therefore, the simulation results conducted for this thesis did not validate the findings from literature regarding the energy savings of LVDC technology compared to LVAC technology.

The difference in the results can be explained by the fact that no DC loads were connected to either simulation model. Since the improvement in energy efficiency regarding the LVDC/LVAC system including DC based DER compared to the LVAC system is dependent on the DC load ratio, the simulated LVAC system was more energy efficient (HuipengLi et al. 2020). The designed system for TSV includes EV charging points that are planned to be connected to the LVDC side of the hybrid LVDC/LVAC system as DC loads, but these were not simulated mainly because the dimensioning of the chargers was still uncertain and partly due to simplifications regarding the simulation, and this had an effect on the simulation results.

Nevertheless, the results from the simulations validate the finding from literature pointing out that the improvement in energy efficiency of the hybrid LVDC/LVAC system including solar PV production compared to the LVAC system is dependent on the DC load ratio (HuipengLi et al. 2020). The verification of this finding shows that the DC load ratio should be considered when designing a hybrid LVDC/LVAC MG system, especially when considering system efficiency as well as profitability. However, it should be emphasized that the examined LVDC system designed for TSV mainly serves the needs of solar PV production and storage. In other words, it transfers the produced solar electricity to the part of the LVDC network where it is needed and thus able to increase the share of self-consumption and self-sufficiency. In practice, this network is not built for loads, even if it includes charging points for EVs. Their power is relatively low compared to the electricity consumption of the whole area.

Another aspect to consider is the peak power and load profile for Tyyssija which were estimated by just using the number of apartments designed for the building and with a typical residential load profile. They will most likely not correspond to reality, thus the amount of DC loads required to reach the DC load ratio threshold will depend greatly on the actual peak power and load profile of Tyyssija.

Due to simplifications, the cables between the four (5A-D) Block 5 buildings on the DC side of the LVDC/LVAC system were not modeled. That being said, modeling these cables might slightly increase the power losses of the hybrid LVDC/LVAC system and thus have effect on the final results.

The electrical structure of the simulated LVAC model and the components that the LVAC model consists of do not exactly correspond to the hybrid LVDC/LVAC model simulated. The LVAC does not have a BSS. Simulating a BSS to the LVAC model would require a bidirectional DC-AC converter compared to the bidirectional DC-DC converter used to connect the BSS to the LVDC side of the hybrid LVDC/LVAC system. As mentioned earlier, inverters (DC-AC) and rectifiers (AC-DC) have lower efficiencies compared DC-DC converters. Therefore, adding a BSS to the LVAC system would increase the use of DC-AC conversion stages, and thus increase the power conversion losses of the system. However, simulating a BSS to the LVAC system would also affect the transformer and cable losses as well, and therefore, a further analysis would require a simulation. Nevertheless, modelling the BSS to both systems might give more comparable results.

Also, the LVAC model does not have a cable between Tyyssija and Block 5 connecting them directly to each other like on the LVDC side of the hybrid model. Since the cable was left out, the surplus solar PV electricity from for example Tyyssija has to travel through the transformers to supply the loads of Block 5, which causes more power losses compared to traveling through the cable connecting the buildings directly. However, LVAC distribution systems are typically not looped, because system protection and safe system operation would become more complex and challenging (Horowitz & Phadke 2014). In this sense, the comparison is made exactly as the system would be implemented in practice with LVAC technology.

Furthermore, the LVAC and the hybrid LVDC/LVDC grids simulated are neither microgrids according to the official definition of a MG. The LVAC is not a MG because no BSS was simulated to it, and therefore it is not capable of operating independently. This is because solar PV inverters without a BSS do not work in the case that the main grid is down, because they are specifically designed to detect grid faults and have anti-islanding protection to prevent them from working when the grid is down (Velasco et al. 2010). Also, the same problem is with the Ferroamp products chosen for the RESPONSE project even though the LVDC system includes a BSS. According to Ferroamp the EnergyHub XL inverter needs the power grid to work, and in the case of a grid failure, it will shut down for safety reasons (Ferroamp 2021e). Despite this, the technical data used represent typical values for inverters and converters in general, and thus do not affect the results from the simulations, and therefore the results are usable for the comparison of LVDC and LVAC technology from the energy efficiency point of view. Yet, for future reference, applying the technical data of inverters and converters, that are capable of working in standalone mode to the simulations, is recommended, because they might give more objective results.

For future reference, the use of another more practical simulation software is recommended for more accurate results, for example MathWorks Simulink. With MathWorks Simulink it is possible to simulate and analyze complex systems accurately and even create own components (MathWorks 2021).

REFERENCES

Aboelsaud, R., Ibrahim, A. & Garganeev, A. G. 2019. Review of three-phase inverters control for unbalanced load compensation. International Journal of Power Electronics and Drive Systems (IJPEDS), Volume 10, Pages 242. Date retrieved 13.5.2021. doi:10.11591/ijpeds.v10.i1.pp242-255.

Ali S. Q., Babar, M. S., Maqbool, S. D. & Al-Ammar, E. A. 2012. Comparative analysis of AC DC Microgrids for the Saudi Arabian distribution system. Date retrieved 21.5.2021. https://doi.org/10.1109/TDC.2012.6281475.

Anand, S. and Fernandes, B. G. 2010. Optimal voltage level for DC microgrids. IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society. Pages 3034-3039. Date retrieved 8.6.2021. doi: 10.1109/IECON.2010.56749.

Bevrani, H., Francois, B. & Toshifumi, I. 2017. Microgrid Dynamics and Control: A Solution for Integration of Renewable Power. John Wiley & Sons. ProQuest Ebook Central. Date retrieved 13.5.2021. https://ebookcentral.proquest.com/lib/turkuamk-ebooks/detail.action?docID=4923381.

Carlstedt, I. 2014. The effects of system voltage in 1 500 VDC solar power systems. Master's Thesis. Electrical Engineering. Helsinki: Aalto University. Date retrieved 18.6.2021. http://www.urn.fi/URN:NBN:fi:aalto-201403061500

Cirino, A. W., Paula, H. de, Mesquita, R. C. & Saraiva, E. 2009. Cable parameter determination focusing on proximity effect inclusion using finite element analysis. 2009 Brazilian Power Electronics Conference, Pages 402-409. Dater retrieved 12.12.2021. doi: 10.1109/COBEP.2009.5347744.

Donev, J., Stenhouse, K., Jenden, J., Hanania, J., Dharan, G. & Afework, B. 2020. Energy Education - Transformer. Date retrieved 5.12.2021. https://energyeducation.ca/encyclopedia/Transformer

Dragičević, T. & Blaabjerg, F. 2017. Chapter 9 - Power Electronics for Microgrids: Concepts and Future Trends. Editor(s): Mahmoud, M. S. Microgrid, Butterworth-Heinemann, Pages 263-279. Date retrieved 1.6.2021. https://doi.org/10.1016/B978-0-08-101753-1.00009-7.

Elsayed, A. T., Mohamed, A. A. & Mohammed, O. A. 2015. DC microgrids and distribution systems: An overview. Electric Power Systems Research, Volume 119, Pages 407-417. Date retrieved 4.6.2021. https://doi.org/10.1016/j.epsr.2014.10.017.

Energiateollisuus 2021. Sähköverkkojen rakenne. Date retrieved 13.10.2021. https://energia.fi/en/energy_sector_in_finland/energy_networks/electricity_networks

Fardo, S. W. & Dale, R. P. 2008. Electricity and Electronics Fundamentals. The Fairmont Press, Inc. ProQuest Ebook Central. Date retrieved 12.12.2021. https://ebookcentral.proquest.com/lib/turkuamk-ebooks/detail.action?docID=3239060.

Ferroamp 2021a. Solar String Optimizer. Date retrieved 19.10.2021. https://ferroamp.com/en/solar-string-optimiser/

Ferroamp 2021b. Energy Storage Optimizer. Datasheet. Date retrieved 5.11.2021. https://ferroamp.com/en/nedladdningar/

Ferroamp 2021c. EnergyHub XL rack. Datasheet. Date retrieved 31.10.2021. https://ferroamp.com/en/nedladdningar/

Ferroamp 2021d. EnergyHub XL wall. Datasheet. Date retrieved 31.10.2021. https://ferroamp.com/en/nedladdningar/

Ferroamp 2021e. Frequently asked questions. Date retrieved 3.12.2021. https://support.ferroamp.com/sv-SE/support/solutions/articles/47001167058-om-man-har-batteri-och-er-energyhub-hur-fungerar-det-vid-ett-str%C3%B6mavbrott-kan-systemet-leva-vidare-

Fingrid 2021a. Electric and magnetic fields. Date retrieved 14.5.2021. https://www.fingrid.fi/en/grid/safety/impacts-of-transmission-lines-on-people/electric-and-magnetic-fields/

Fingrid 2021b. Maintenance of power balance. Date retrieved 14.5.2021. https://www.fingrid.fi/en/grid/power-transmission/maintenance-of-power-balance/

Francés, A., Asensi, R., García, Ó., Prieto, R. & Uceda, J. 2018. Modeling Electronic Power Converters in Smart DC Microgrids—An Overview. In IEEE Transactions on Smart Grid, Volume 9, No. 6, Pages 6274-6287. Date retrieved 6.5.2021. doi: 10.1109/TSG.2017.2707345.

Fregosi, D., Ravula, S., Brhlik, D., Saussele, J., Frank, S., Bonnema, E., Scheib, J., Wilson, E. 2015. A Comparative Study of DC and AC Microgrids in Commercial Buildings Across Different Climates and Operating Profiles. 2015 IEEE First International Conference on DC Microgrids (ICDCM), Pages 159-164. Date retrieved 6.5.2021. doi: 10.1109/ICDCM.2015.7152031.

Gerber, D. L., Vossos, V., Feng, W., Marnay, C., Nordman, B. & Brown, R. 2018. A simulation-based efficiency comparison of AC and DC power distribution networks in commercial buildings. Applied Energy, Volume 210, Pages 1167-1187. Date retrieved 17.5.2021. https://doi.org/10.1016/j.apenergy.2017.05.179.

Gerber, D. L., Musavi, F., Ghatpande, O. A., Frank, S. M., Poon, J., Brown, R. E. & Wei Feng. 2021. A Comprehensive Loss Model and Comparison of AC and DC Boost Converters. Energies 2021, 14, no. 11: 3131. Date retrieved 13.12.2021. https://doi.org/10.3390/en14113131

Horowitz, S. H. & Phadke, A. G. 2014. Power system relaying. 4th ed. Chichester, West Sussex: John Wiley and Sons.

HuipengLi, Li, S., Wang, T., Wang, X., Chang, X., Zhang, M. & Meng, R. 2020. A Comparison of Energy Ein AC and DC Microgrid with New Energy. IOP Conference Series: Earth and Environmental Science. 619. 012057. Date retrieved 6.5.2021. doi: 10.1088/1755-1315/619/1/012057.

IEA 2021. World Energy Outlook 2021: Executive summary. Date retrieved 13.12.2021. https://www.iea.org/reports/world-energy-outlook-2021/executive-summary

Jovcic, D. & Ahmed, K. 2015. High voltage direct current transmission: Converters, systems and DC grids. Hoboken: John Wiley & Sons Limited.

Justo, J. J., Mwasilu, F., Lee, J. & Jung, J. 2013. AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renewable and Sustainable Energy Reviews, Volume 24, Pages 387-405. Date retrieved 6.5.2021. https://doi.org/10.1016/j.rser.2013.03.067.

Manandhar, U., Ukil, A., & Kiat Jonathan, T. K. 2015. Efficiency comparison of DC and AC microgrid. 2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA), Pages 1-6. Date retrieved 6.5.2021. doi: 10.1109/ISGT-Asia.2015.7387051.

MathWorks 2021. Simulink. Date retrieved 29.11.2021 https://uk.mathworks.com/products/simulink.html

Mertens, K. 2014. Photovoltaics: Fundamentals, technology, and practice. Chichester, West Sussex, United Kingdom: Wiley.

Mutanen, A., Lummi, K. & Järventausta, P. 2019. Valtakunnallisten tyyppikäyttäjämäärittelyiden päivittäminen ja hyödyntämisen periaatteet verkkopalvelumaksuihin liittyvissä tarkasteluissa. Tampere: University of Tampere. Date retrieved 6.5.2021. https://docplayer.fi/143037259-Valtakunnallisten-tyyppikayttajamaarittelyiden-paivittaminen-ja-hyodyntamisen-periaatteet-verkkopalvelumaksuihin-liittyvissa-tarkasteluissa.html#show_full_text

Mäkelä, M. 2005. Tekniikan kaavasto: Matematiikan, fysiikan, kemian ja lujuusopin peruskaavoja sekä SI-järjestelmä. Page 120. Tampere: Amk-kustannus : Tammertekniikka.

Peyghami, S., Mokhtari, H. & Blaabjerg, F. 2017. Chapter 3 - Hierarchical Power Sharing Control in DC Microgrids. Editor(s): Mahmoud, M. S. Microgrid, Butterworth-Heinemann, Pages 63-100. Date retrieved 1.6.2021. https://doi.org/10.1016/B978-0-08-101753-1.00003-6.

Planas, E., Andreu, J., Garate, J. I., Alegria, I. M., Ibarra, E. 2015. AC and DC technology in microgrids: A review. Renewable and Sustainable Energy Reviews, Volume 43, Pages 726-749. Date retrieved 21.5.2021. https://doi.org/10.1016/j.rser.2014.11.067.

PowerFactory 2021. PowerFactory Applications. Date retrieved 15.10.2021. https://www.digsilent.de/en/powerfactory.html

Prysmian Group 2018. AMCMK 0,6/1 kV. Date retrieved 9.12.2021. https://fi.prysmiangroup.com/sites/default/files/business_markets/markets/downloads/datasheets/cpr%20AMCMK%200%2C6_1kV_180118.pdf

PVGIS 2019. European Commission – Photovoltaic Geographical Information System (PVGIS). https://re.jrc.ec.europa.eu/pvg_tools/en/#MR

Semënov, D., Mirzaeva, G., Townsend, C. D., Goodwin, G. C. 2017. A battery storage control scheme for AC microgrids. Conference publication. School of Electrical Engineering and Computer Science. Australia: The University of Newcastle. Date retrieved 28.5.2021. doi: 10.1109/ICEMS.2017.8056512.

Shahbazi, M. & Khorsandi, A. 2017. Chapter 10 - Power Electronic Converters in Microgrid Applications. Editor(s): Mahmoud M. S. Microgrid, Butterworth-Heinemann, Pages 281-309. Date retrieved 1.6.2021. https://doi.org/10.1016/B978-0-08-101753-1.00010-3.

Sharkh, S. M., Abu-Sara, M. A., Orfanoudakis, G. I. & Hussain, B. 2014. Power Electronic Converters for Microgrids. Singapore: John Wiley & Sons. Date retrieved 13.5.2021. https://dx.doi.org/10.1002/9780470824054.

Sivakumar, S., Sathik, M. J., Manoj, P. & Sundararajan, G. 2016. An assessment on performance of DC–DC converters for renewable energy applications. Renewable & sustainable energy reviews, Volume 58, Pages 1475-1485. Date retrieved 18.5.2021. doi:10.1016/j.rser.2015.12.057

SMA 2021a. Sunny Tripower 8.0 – 10.0. Datasheet. Date retrieved 25.5.2021. https://www.sma.de/en/products/solarinverters/sunny-tripower-80-100.html

SMA 2021b. Sunny Tripower 15000TL / 20000TL / 25000TL. Datasheet. Date retrieved 23.10.2021. https://www.sma.de/en/products/solarinverters/sunny-tripower-15000tl-20000tl-25000tl.html

Suomi, M. 2010. Effect of Screen Cross-Section on Ampacity of 60 – 400 kV High-Voltage Cable. Bachelor of Science Thesis. Electrical Power Engineering. Helsinki: Metropolia University of Applied Sciences. Date retrieved 1.11.2021. http://www.urn.fi/URN:NBN:fi:amk-201004166526

Tan L., Wu B., Rivera S. & Yaramasu V. 2016. Comprehensive DC Power Balance Management in High-Power Three-Level DC–DC Converter for Electric Vehicle Fast Charging. In IEEE Transactions on Power Electronics, Vol. 31, Issue 1, Pages 89-100. Date retrieved 4.12.2021. doi: 10.1109/TPEL.2015.2397453.

Turun karttapalvelu 2021. Turun kaupunki – Turun karttapalvelu. Date retrieved 6.11.2021. https://opaskartta.turku.fi/IMS/fi/Map

TYS 2021. TYS - Ylioppilaskylän uusi sydän tulee tarjoamaan monipuolisia palveluita ja ilmastoystävällistä asumista. Date retrieved 5.12.2021. https://tys.fi/tyyssija

Unamuno, E., Barrena, J. A. 2015. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. Renewable and Sustainable Energy Reviews, Volume 52, Pages 1251-1259. Date retrieved 6.5.2021. https://doi.org/10.1016/j.rser.2015.07.194.

Velasco, D., Trujillo, C. L., Garcera, G., Figueres, E. 2010. Review of anti-islanding techniques in distributed generators. Renewable and Sustainable Energy Reviews, Volume 14, Issue 6, Pages 1608-1614. Date retrieved 30.11.2021. https://doi.org/10.1016/j.rser.2010.02.011.

Wood, E. 2020. What is a Microgrid. Microgrid Knlowledge 28.3.2020. Date retrieved 13.5.2021. https://microgridknowledge.com/microgrid-defined/

Äijö, T. 2019. 1500 V DC/DC-converter for Connecting Battery Energy Storage and Solar Electricity System. Master of Science Thesis. Faculty of Information and Electrical Engineering. Tampere: Tampere University. Date retrieved 13.5.2021. https://trepo.tuni.fi/bitstream/handle/123456789/27089/Aijo.pdf?sequence=4&isAllowed=y