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Feasible DC voltage levels in households

One potential area to boost the PV integration: direct DC supply in buildings

Master's thesis in Electric Power Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Some of the advantages that AC systems used to have back in the 20th century are no longer applicable, as DC/DC converters are able to boost or buck the voltage efficiently. Therefore, nowadays DC systems are more efficient and economic than they were before, and they are the most logical solution for nowadays trends, in every aspect of the present electricity system model.

Consequently, if the amount of DC loads is increasing and so is the DC generation in general, but mainly the case of household electricity production, why not avoid the DC/AC/DC conversion losses? This is what is known as Low Voltage Direct Current (LVDC) distribution.

In this Master Thesis work, the electrical distribution system of a generic household has been modelled, as well as the load profiles, and different voltage levels have been considered in order to compare the results obtained, both in terms of efficiency and cost.

The results of this thesis work show the pros and cons of having one or multiple voltage levels. Higher voltage levels lead to lower currents and, therefore, lower conduction losses, whereas the risk of electric shock is higher than when lower voltage levels are chosen. However, the conduction losses when having lower voltage levels are higher than the ones due to rectification, so it would not be feasible to choose DC for the distribution system in this case.

All in all, more research is still required in order to develop standards on DC distribution systems in households, on which organizations such as IEC (International Electrotechnical Commission) are currently working.

Keywords: DC distribution, solar PV, household, efficiency

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María Cristina Moreno Sánchez, Gothenburg, 2018

Contents

1 Introduction

This chapter introduces the background to the direct DC supply from solar PV power of households. It describes the aims, problem tasks, scope and timetable that were used in studying the topic of solar PV power integration. It depicts the structure of the thesis report.

1.1 Background

Today, most electricity distribution is done via AC whereas more and more products rectify this AC to run on DC. If power supply was directly on DC, the rectification losses would be overcome.

Moreover, solar PV electricity generation is still a small contributor to the total electricity production in Sweden. Despite its exponential growth world-wide, less than 0.5% of the generated electricity in 2017 came from solar PV. Direct DC supply in buildings is one potential area to boost the PV integration, as it would overcome the DC/AC/DC conversion losses.

This project studies what voltage levels are feasible for direct DC distribution in a conventional household, which is simulated in RISE's Research Villa in Borås. Therefore, the results of this study will be tested.

1.2 Preliminary Aim

The aim of this thesis is to investigate the feasible DC voltage levels for a conventional household in terms of optimal performance and life-cycle cost (LCC).

1.3 Scope and Method

The tasks included in this project are:

1. Literature reviewing of previous studies of local DC distribution for households.

2. Study current legal framework and standards for DC distribution in households and commercial products.

3. Development of a tool which simulates the distribution system in a conventional household, based on the Research Villa.

4. Estimation of the load profiles of a conventional household.

5. Determine the losses and cable usage when using various DC-voltage levels, as well as combinations of them, for instance 20, 54 and 380 V.

6. Feasibility analysis of electrical performance for the calculated cases and LCC evaluation.

7. Utilization of USB cables to power electric devices on DC.

8. Writing the report.

9. Oral presentation.

Matlab is the software used for this study.

2

Literature Review

This chapter explains why most electric systems are AC instead of DC in most electric systems, the differences between both types of systems and the present situation. Is the so-called "War of Currents" really over?

2.1 The origin of AC electric systems

In the 1880s decade, Thomas Edison and Nikola Tesla together with George Westinghouse were adversaries in the so-called War of Currents. Edison promoted direct current (DC) for the electric power distribution, whereas Tesla and Westinghouse advocated alternating current (AC).

The main disadvantage of Edison's project was that DC could not be easily converted to different voltage levels. Therefore, the DC system generated and distributed electric power at the same voltage as it was used by consumers, which required the use of large and costly distribution wires, as the current was relatively high. Moreover, a short distance between generating plants and loads was needed in order to minimize the losses.

This problem was solved using transformers which operate on alternating current (AC). Relatively small and cheaper distribution wires could be used to send AC power at high voltage levels over much longer distances. Hence, AC generating stations could be larger and cheaper to send to the consumers.

There was commercial rivalry between the Edison and Westinghouse companies due to the patents that protected the competing systems. Edison, feeling threatened by the rise of AC, carried out a publicity campaign highlighting the safety issues of high voltage transmission, trying to protect his patents and discredit AC.

However, Westinghouse won the contract to supply electricity to the 1893 World's Fair in Chicago, beating Edison's bid, which was unable to power the fair at a lower price. This event turned into a showcase of Tesla's system and later on that same year, Westinghouse received a contract of an important project: the first hydro-electric power plant in the world, powered by Tesla's AC electricity. In 1896, the

Niagara Falls Power Plant started delivering electricity to Buffalo, New York, 26 miles away. The success was considered as the unofficial end to the War of the Currents, and AC became dominant in the electric power industry. In the 1900s Three Phase AC power is fully established as the principle source of electric power usage for the world.

References: [1] [2] [3] [16]

2.2 Present situation

Some of the advantages that AC systems used to have back in the 19^{th} century are no longer applicable, as DC converters are able to boost or buck the voltage efficiently. Therefore nowadays DC systems are more efficient and economic than they were before, and also they are the most logical solution for nowadays trends, in every aspect of the present electricity system model: generation, transmission, distribution and consumption.

When it comes to power transmission, one of the main problems with AC systems is the reactive power, which produces losses and has to be compensated in order to prevent congestion of transmission lines and allow the utilization of their full potential. The advances in technology, particularly in power electronics, have made the conversion from AC to DC efficient. This along with the fact that there is no reactive power or skin effect in DC, and that the difference between the peak value and the average value are negligible in DC, are the main arguments in favor of HVDC lines.

As to power consumption, we are currently living in a DC world. Most of our electronic and battery driven devices use DC: power electronics to control drives of heating, ventilation, LED lighting and PV power systems all operate internally with DC supply voltages. Also, multimedia, mobile phones, IT equipment, electric vehicles, and soon washing machines, fridges, fans and cooling systems can favourable be operated on DC as well, as DC motors allow speed control and higher energy efficiency. So far, this issue is solved by rectifying AC power from the grid, and in the conversion process, energy is unnecessarily wasted.

Last but not least, power generation was traditionally centralized: large power plants would produce electricity and long HVAC transmission lines would transport it to substations, where it would be converted to lower voltage levels and distributed to consumers. However, the increasing consciousness of the human impact on the environment and the lack of fossil fuels in the near future are boosting the development of sustainable energy production sources. Solar and most wind energy converters yield DC and is currently converted to AC to be converted again to DC in order to power DC-driven devices. Moreover, solar PV panels on roofs and the installation of small wind or micro-hydro turbines allow the generation of electricity very closely to where it is consumed. This is what we call local or distributed generation. With DC power generation and storage, individual buildings can achieve autonomy from the public electricity, trade-in surplus power and buy additional electricity as needed. This is also possible with AC generation, but if the generation, consumption, distribution and storage are in DC then we would avoid the AC/DC conversions and therefore saving energy.

Consequently, if the amount of DC loads is increasing and so is the DC generation in general, but mainly the case of household electricity production, why not avoid the DC/AC/DC conversion losses, and therefore reduce the total conversion losses? This is what we call Low Voltage Direct Current (LVDC) distribution. Not only is LVDC the next natural step in electric power systems development, but also a way to ensure universal access to sustainable electricity generation.

References: [4], [10], [11], [13], [14]

2.3 Future challenges

AC oscillates over time, changing its flow direction periodically, whereas DC is constant and always flows in the same direction. Therefore shifting from AC to DC involves several changes in the system. The main ones are explianed below.

2.3.1 Switches and sockets

DC lighting has two main advantages when compared to AC lighting: DC lighting is more efficient and it can give real life light outputs approaching from seven to ten times higher than the equivalent AC incandescent lamps [5]. However, the switches required in DC need to break the circuit faster than in AC because the arc can last much longer before being extinguished, which leads to pitting of switch contacts, overheating and premature failure of the switch, or even fire, [6].

As for sockets, the so-called smart sockets allow to plug in different devices with different voltage levels requirements, [7]. This sockets are smaller compared to the conventional DC outlets, they guarantee a safer operation and they make the diverse electricity availability more economical. However, the main advantage is that they perform DC/DC conversion with desired voltage levels, as they have six-pin configurations for different voltage levels, depending on the requirements of the device connected. This is a convenient and manageable solution for DC sockets with DC distribution in a conventional household.

2.3.2 Protections

When it comes to protection devices such as fuses and circuit breakers, sometimes the ones designed for AC can be directly used in DC systems. When a fault occurs, an arc is created. In order to extinguish it when the current becomes zero, the dialect strength across the arc has to be increased, which can be achieved by cooling the arc, pressurizing the arc, stretching the arc and introducing fresh air. If the voltage over the extinguished arc (recovery voltage) builds up faster than the dielectric strength, the arc can reignite. Therefore, the mechanisms of current interruption take advantage of the natural zero crossing of the alternating current.

However, the fault current in DC systems will not naturally cross zero so, in order to ensure the clearing of the fault, circuit breakers must be connected in series, so that the arc voltage is sufficient. Otherwise, a new design of protection devices is required. Currently there are electromechanical circuit breakers specifically designed for LVDC systems available, even though there are still some issues that must be addressed such as the coordination of these devices.

2.3.3 Wiring

Another factor to take into account would be the wiring. Firstly, the size of the cable depends on the voltage level. In this work, a LVDC distribution system for a single-family house is considered, in which we will have up to two different voltage levels. The wires required depend on the current they need to send, and the current depends on the voltage level of the bus of the distribution system of the house. Therefore, higher voltage levels lead to lower currents, which lead to thinner cables required. Also, the conduction losses are directly proportional to the square of the current, so the lower the current is, the lower the losses will be.

For the 380 VDC bus voltage, there are three standard cable voltage ratings. First, cables for 1-phase DC grids with ± 190 VDC nominal voltages with respect to protective earth requires cables with “300/500 V” voltage rating (line-to-earth / line-to-line). Second, cables for 1-phase DC grids connected to one phase of 2-phase DC grids with +380 VDC nominal voltage with respect to protective earth requires cables with “450/750 V” rating. Third, cables for 2-phase DC grids with ± 380V DC nominal voltages with respect to protective earth require cables with “0.6/1 kV” rating.

For the 20 VDC bus voltage, USB-C cables will be considered. Lower voltage levels lead to higher conduction losses due to Joule’s effect, which means that they could overheat behind the walls. However, if USB-C cables are used as part of the DC distribution system of a building, this problem will be solved by increasing the cross section and coating of the wire.

2.4 Integration of future LVDC distribution systems

2.4.1 Architectures

Many different appliances can use LVDC distribution systems, and there is a different solution for each one of them. The system's architecture can be classified in three main categories, depending on its power or voltage level.

Firstly, single bus topology is the simplest: two wires supply the voltage at the point of load. Moreover, the power converter is reliable as fault protection. This architecture is applied both in automotive (12VDC) and telecomunication (48VDC) industries.

Secondly, the three-wire bipolar configuration brings advantages for LVDC distribution in buildings, such as a lower voltage level with respect to the ground required, which means more safety; and also it offers three different voltage levels: +VDC, -VDC and 2VDC. This configuration on AC is used in USA: +110 VAC, -110 VAC.

Last, multibus configuration is used when redundant distribution buses are needed. It increases both reliability and availability, and it allows the connection of microgrid clusters so that the power exchanges can be controlled by controlling the local voltage set points. When the systems requires higher reliability and flexibility during faults and maintenance periods, a reconfigurable topology can be used: in a mesh or ring configuration all the elements connected are bidirectional, and in a zonal configuration each element is connected to different buses.

2.4.2 Voltage levels

DC loads can be divided in three groups, considering their voltage or power level:

1) Low power loads: 24-48 VDC, less than 0.4 kW: electronic equipment and devices, mostly placed in bedrooms, living rooms ad out door areas. These voltage levels could be supplied in these rooms maximizing efficiency and safety.

2) Medium power loads: 230-400 VDC, 0.4-10 kW: kitchen appliances and laundry rooms. 230 VDC devices have the same current loading in the wires as 230 VDC. Higher voltage level means higher efficiency as there is a wire-gauge reduction. However, the voltage level should not be higher than 400 VDC because the efficiency difference is not worth it as the protection system is too demanding.

3) High-power elements: voltage levels higher than 538VDC, and power levels higher than 10 kW: common facilities such as elevators and heating or cooling systems.

References: [9], [14], [23]

In table 2.1, different voltage levels and their advantages are studied, [].

Table 2.1: DC Voltage Levels

Voltage level	Advantage
VDC⩾565	Direct interconnection with 3-ph, 400 VAC grid
380-400 VDC	Standard in data-center industry
325 VDC	Minimum modification required for loads with input rectifier
230 VDC	Compatible with pure resistive loads
120 VDC	Limit for extra-LV definition, no need for protection system against indirect contacts
48 VDC	Standard in telecomunication industry
24 VDC	EMerge Alliance Occupied Space Standard
12 VDC	Standard in automotive industry

According to [14], this is a summary of reasoning to select a voltage level:

Table 2.2: Summary of reasoning to select a voltage level

Voltage level	Reasoning
$VDC \geqslant 220$	Adaptability with existing building's grid
$VDC \leqslant 238$ or 457 (ph-to-ph)	Compatibility with single phase loads
$463 < VDC < 617$	Compatibility with 3-phase loads
Maximum possible	Efficiency
$VDC \leqslant 373$	Insulation
$VDC \leqslant 350 - 450$	Component and devices matching (rated levels)

2.4.3 Integration of future LVDC distribution systems

There are two LVDC systems proposed as best solutions. The first one would be a unipolar bus of 380-400 VDC, which has the following advantages: it is simple, as the architecture requires only two wires to supply the voltage; it is convenient, as the voltage levels are the equivalent to the present AC voltage, so the current loading in the wires is the same as 230 VAC; and efficient, as higher voltage means less losses and also there are no conversion stages as the whole system from generation to consumption is DC.

The second solution suggested is a bipolar bus with +/-750 VDC, with the possibility to extract a second-level +/-375 VDC, which fits the required voltage levels for both medium and high power appliances in the building. The IEC 60038 standard sets the upper limit for LVDC systems at 1500 V, so the voltage levels previously mentioned are the best ones in order to maximize the efficiency in the distribution.

As the Research Villa is a single-family home, no common facilities are needed, the highest voltage levels are not required. Therefore, in order to maximize both efficiency and safety, one possible solution could be a bipolar bus with +/-380 VDC. Apart from that, in this project the feasibility of adding two more DC buses is going to be studied.

2.4.4 USB-C

The lowest voltage level of the three DC buses suggested for the Research Villa would be 20 V DC. This is because of the so-called "the connector of the future": it is an emerging standard for charging and sending data. This new connector is smaller, bidirectional and reversible, makes it easier to plug in. USB-C cables can carry up to 100 W (20 V and 5 A), so they can charge larger electronic devices, such as laptops and LDC TV's. Another advantage is the transfer speed they offer: they double the bandwidth of USB 3 at 10 Gbps. Finally, standards are backward compatible, so adapters can be used with older devices, [19].

One of the potential benefits of the USB-C standard when it comes to smart grid applications is by integrating the battery-powered electronic devices as a small-scale energy storage. The bidirectional feature of this standard allows the power flow to be reversed and supply power to the grid or other parts of the building: an estimated three billion devices globally connected through USB-C in 2019 would be able to supply a lot of energy to the grid if needed. However, these energy flows will need to be controlled and aggregated, and Ochno's Cloud Socket is a solution designed for office buildings, public buildings or households, [20].

Moreover, the USB-C allows the data transfer, so they can be used as part of a wired communication system in a smart building. This kind of communication systems are more reliable and less sensitive to interference, [21]. In this way, having a distribution system with USB-C cables would also allow to control the devices connected to it and therefore a more efficient use of energy. For instance, if the dishwasher had a USB-C output connected to the USB-C distribution system, using your own smart phone you could start it by connecting to the control unit of the communication system, and the data would be transferred by the same wires as used for power supply for the loads connected to the low voltage bus.

3
Case Study

3.1 Introduction

3.1.1 The Research Villa Project

The Research Villa is a single-family house located in Borås, a Swedish city in the province of Västergötland, in the West of the country, where the main facilities of RISE (Research Institute of Sweden) are located. In this house, all the loads of a four-member family are simulated: from lighting to heating and cooling systems.

The villa is equipped with all kinds of sensors so that it is possible to keep track of the main variables required in order to model the power demand of a generic house with the characteristics of an average Swedish family. Moreover, different kinds of tests are carried out, in order to study the load profiles and their performance under specific situations that might be interesting for different studies.

3.1.2 Present Electrical Installation

The Research Villa has solar PV panels and it is also connected to the grid. In the future it will include a battery storage system as well. Both solar PV panels and the battery storage system provide power in DC, but it has to be converted to AC in the Teknik room, where the utility grid connection point is, so that all the power is distributed throughout the house in AC.

In this work, exclusively the distribution system is taken into account. Whether the power comes from the grid or the solar PV panels is not considered: in this model it is considered that the power comes from the connection point to the utility grid in the voltage level of the distribution system and then it is distributed throughout the house.

3.2 Voltage Levels of Study

There are no standards on DC voltage levels in households yet, organizations such as IEC (International Electrotechnical Commission) are currently working on them, [9], [12], [16], [22], [24]. However, we know the ranges where those standards will be, as explained in section 2.4.2.

The case base is the present situation: 230 VAC, as shown in figure 3.1. The losses considered in this work are marked in the figure and explained in section 3.6.

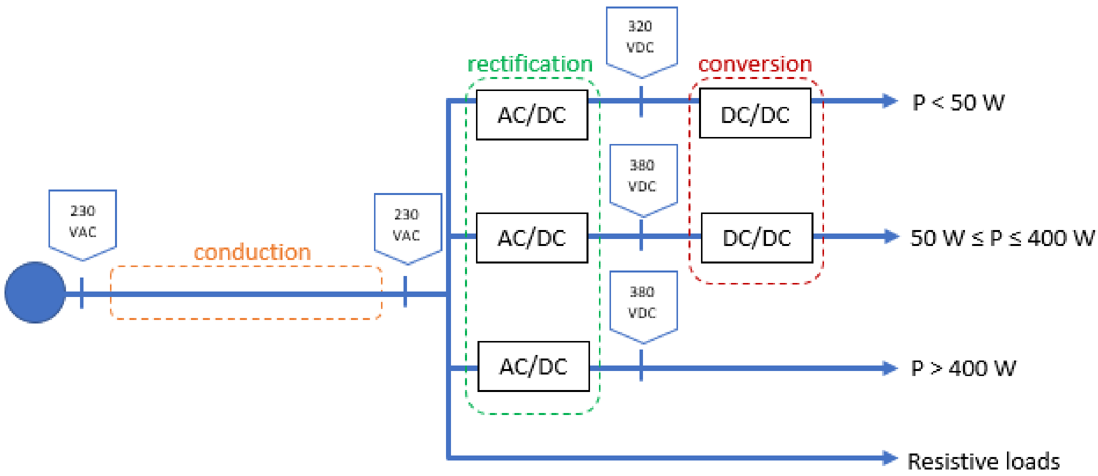


Figure 3.1: Scenario 1: 230 V AC

Considering safety, compatibility, efficiency and cost, the most chosen voltage level in the literature is 380 V DC, [8], [9], [17]. Therefore this is the voltage level that has been used for the high voltage bus, as it is required for the most power-demanding loads, such as kitchen and laundry facilities and heating and cooling systems. This scenario is shown in figure 3.2.

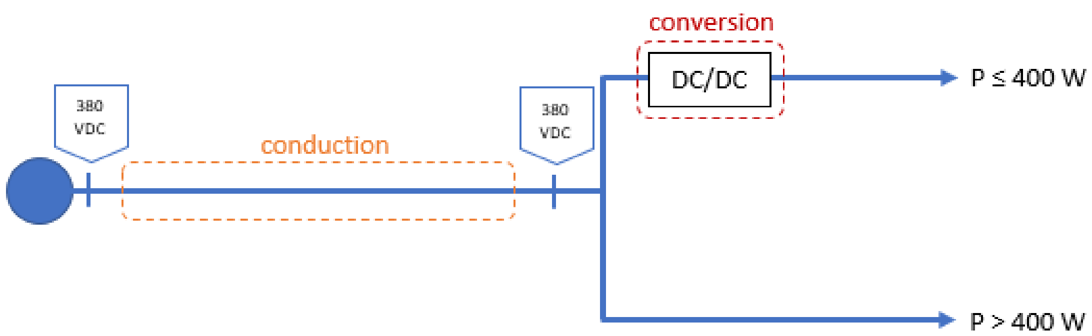


Figure 3.2: Scenario 2: 380 V DC

However, 380 V DC is higher than needed for most appliances such as electronic devices, and a lower voltage level would be safer in rooms where the power demand is lower, such as bedrooms or living rooms. SELV stands for Safety Extra Low Voltage, and it is a defined safe level established 60 V DC, [15]. Therefore a second voltage level below this limit has been considered: 54 V DC, so that there is a margin below 60 V DC in case there are some overvoltages. The structure of Scenario 3 is shown in figure 3.3.

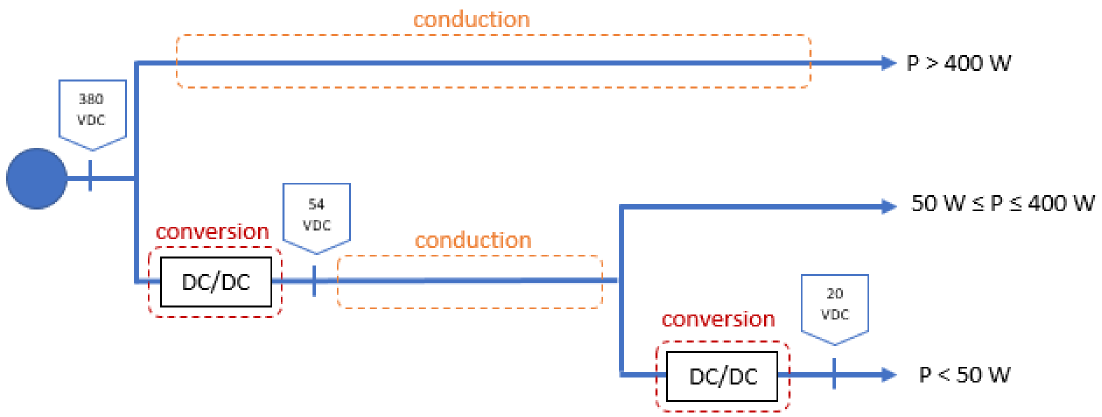


Figure 3.3: Scenario 3: 380 V DC & 54 V DC

Finally, the feasibility of having USB-C sockets on walls has been studied: low voltage level bus of 20 V DC and power demands lower than 100 W.

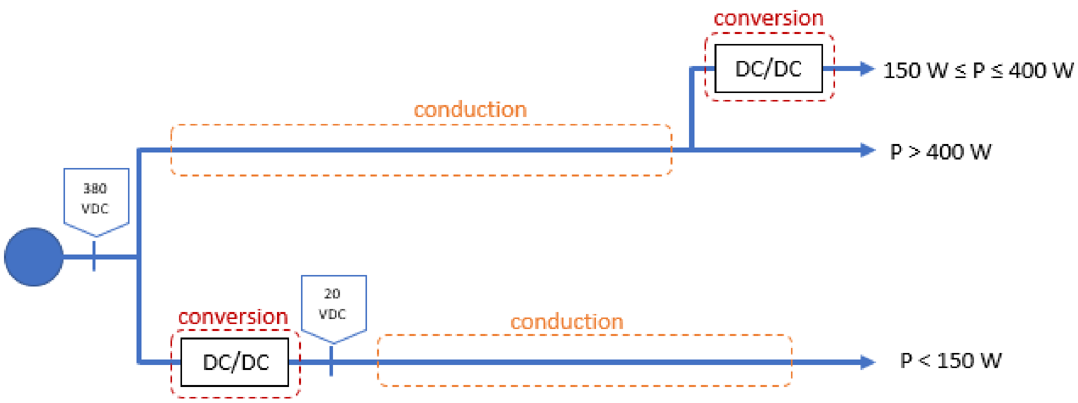


Figure 3.4: Scenario 4: 380 V DC & 20 V DC

These three DC scenarios have been compared to the present AC scenario.

3.3 Loads

3.3.1 Layout

The model is based on the electrical installation plans of the Research Villa, which can be found in Appendix 1 of this report. The house has two floors and sixteen rooms or areas in total: nine in the first floor and seven in the second one. Consequently, the layout of the loads in the model developed corresponds with the one in the actual house. In tables 3.1 and 3.2, the sockets and lighting switches in each room are shown.

Notice that Balkong is presented as a room of the house but it does not have switches or sockets. This is because the switch to the lights in this area of the house is actually the same switch that turns on the outdoors lights, which is physically located in Vindfång. This is explained in section 3.3.2.1.

Table 3.1: Layout of loads. First floor.

Room number	**Room name**	**Loads**
1	Vindfång	3 lighting switches 1 high power socket 2 low power sockets
2	Entré	1 lighting switch 1 high power socket 4 low power sockets
3	KLK1	1 lighting switch 1 high power socket
4	Teknik	1 lighting switch 13 high power socket
5	Vardagsrum	2 lighting switch 1 high power socket 5 low power sockets
6	Pentry	3 lighting switches 8 high power socket
7	Uterum	1 lighting switch 1 high power socket 2 low power sockets
8	KLK2	1 lighting switch
9	HWC	2 lighting switches 1 high power socket

Therefore there are 24 lighting switches, 33 high power sockets and 28 low power sockets in total. This division between "high" and "low" power sockets is important because when there are two voltage levels in the distribution system, the high power sockets are connected to the high voltage bus, and the low power sockets are con-

Table 3.2: Layout of loads. Second floor.

Room number	Room name	Loads
10	Stairs + Entré	2 lighting switches 1 high power socket 1 low power socket
11	Allrum	2 lighting switches 1 high power socket 2 low power sockets
12	Badrum	2 lighting switches 1 high power socket
13	Sovrum1	1 lighting switch 1 high power socket 4 low power sockets
14	Sovrum2	1 lighting switch 1 high power socket 4 low power sockets
15	Sovrum3	1 lighting switch 1 high power socket 4 low power sockets
16	Balkong	0 lighting switches

nected to the low voltage one. In Appendix 1, high power sockets are marked in blue and the low power sockets are marked in green.

3.3.2 Loads and Classification

In table 3.3 the different groups of loads considered and the loads that they include are shown. The power demand values are the actual ones from the appliances in the inventory of the Research Villa.

The loads have been classified in four groups: lighting, resistive loads, large appliances and small appliances. The resistive loads are the ones that do not need rectifiers as they can run both on AC and DC. Consequently, the rest of loads need rectifiers when the distribution system is on AC. Loads with a power demand greater than 400 W are considered as big appliances and are connected to the high power sockets, and the rest are considered as small appliances and are connected to the low power sockets.

3.3.2.1 Lighting

The distribution system for the lighting cables is different from the one for the rest of the loads, as these cables are above the ceiling instead of behind the walls. Two

Table 3.3: Loads

Group of loads	Symbol	Name of the Load	Power [W]
Lighting	L1	outdoors wall light	6
	L2	indoors wall light	4
	L3	bright eye	6.7
	L4	ceiling light	10
	L5	sink led	4
	L6	post light	12
Resistive loads	Ov	oven	3600
	K	water kettle	2400
	WMr	washing machine's resistance	2000
	Dr	clothes dryer's resistance	1930
	HDr	hairdryer's resistance	1800
	DWr	dishwasher's resistance	1740
	CM	coffee machine	1100
	Tst	bread toaster	860
Large appliances	Stv	stove	7200
	HP	heat pump	2400
	M	mixer	1400
	VC	vaccum cleaner	1100
	MO	microwave oven	900
Small appliances	WMm	washing machine's motor	300
	DWm	dishwasher's motor	300
	Dm	clothes dryer's motor	270
	HDm	hairdryer's motor	260
	FTX	air system	900
	F	fridge	160
	VGC	video game console	130
	TV	television	90
	PC	laptop	80
	CH	cooker hood	70
	CP	circulation pump	40
	R	router	12
	L	lamp	10
	Ph	cell phone	3

assumptions have been made here, as explained below.

The first assumption made is splitting the cables into two groups, which have been called "Lighting Thicker Cables" and "Lighting Thinner Cables". The first group of cables transport the power from Teknik room to what I have called "nodes". Each node brings power to a room or two, depending on the power demand of the lights of the room, as it is shown in table 3.4. These add up to 13 "Lighting Thicker Cables". The second group of cables are the ones that transport the power from each node to each light of that room or rooms.

The second assumption made is that every lighting switch turns on all the lights of a certain type in the same room. In other words, there are as many switches in each room as different types of lights in that room. These add up to 24 switches in the house. Therefore, all the cables that go from each node to each type of light have been grouped together and considered as one longer cable. For example, if in a room there are three lights type A, instead of considering three independent cables from the room to each one of the lights, one cable whose length is the addition of the lengths of the three independent cables is considered. This makes the calculations easier and the result is the same because the power transported by all the cables in the same group is the same. Also, regarding this second assumption, notice that it has been considered that all the outdoors lights have a common switch, which is located in Vindfång.

Table 3.4: Types of lights in each room

Node	**Type**	**Quantity**	**Max power [W]**	**Feeder length [m]**
1. Vindfång + Balkong	L1 L3 L6	5 6 2	94.2	66
2. Entré + KLK1	L3	9	94.2	68
3. Teknik	L4	3	30	10
4. Uterum	L3	9	53.6	90
5. Vardagsrum	L3 L4	11 2	93.7	100
6. Pentry	L3 L4 L5	5 1 1	47.5	100
7. HWC + KLK2	L3 L4 L5	6 6 2	54.2	140
8. Stairs + Entré	L2 L3	2 2	21.4	65
9. Allrum	L3 L4	5 1	43.5	50
10. Badrum	L3 L5	5 1	37.5	40
11. Sovrum1	L3	3	20.1	46
12. Sovrum2	L3	3	20.1	100
13. Sovrum3	L3	3	20.1	90

The 24 switches are shown in table 3.5. As it has been mentioned before, there is a switch for each light of each room. Notice that the feeder lengths of the "Lighting Thinner Cables" are the addition of the individual cables from each knot to each light in the same room.

Table 3.5: Switches in each room

Room	Switch	Light	Max power [W]	Feeder length [m]
1. Vindfång + Balkong	1.1	L1	6	200
	1.2	L3	6.7	60
	1.3	L6	12	120
2. KLK1	2.1	L3	6.7	20
3. Entré	3.1	L3	6.7	100
4. Teknik	4.1	L4	10	100
5. Uterum	5.1	L3	6.7	215
6. Vardargsrum	6.1	L3	6.7	540
	6.2	L4	10	110
7. Pentry	7.1	L3	6.7	125
	7.2	L4	10	25
	7.3	L5	4	50
8. HWC	8.1	L3	6.7	22
	8.2	L4	10	20
9. KLK2	9.1	L4	10	20
10. Stairs	10.1	L2	4	62
	10.2	L3	6.7	24
11. Allrum	11.1	L3	6.7	150
	11.2	L4	10	20
12. Badrum	12.1	L3	6.7	90
	12.2	L5	4	18
13. Sovrum1	13.1	L3	6.7	72
14. Sovrum2	14.1	L3	6.7	80
15. Sovrum3	15.1	L3	6.7	80

3.3.2.2 Purely resistive loads

This group of loads include those loads that are purely resistive. Notice that in table 3.3, the power demanded by the washing machine, the clothes dryer, the hairdryer and the dishwasher is divided into two groups: resistive and large appliances. This is because there some of the power is dissipated in resistances in order to produce heat through Joule's effect, and the rest is the needed to power the electric motor, as well as other electronics in the device.

Also, notice that the power demanded by the resistances of these appliances is in the range of ten times higher than the power demand of the electric motors, so these ones are included in the small appliances group of loads. However, when it comes to connecting each load to the low or high voltage level bus, the total power demand of these loads is calculated and connected to the high voltage level bus.

3.3.2.3 Large appliances

As it has been mentioned before, the rest of the loads have been divided into two groups, depending on their power demand, so that the loads with a power demand lower than 400 W can be connected to the low voltage level bus, and the rest can be connected to the high voltage one.

There are 33 high power sockets, as shown in tables 3.6 and 3.7. Notice that, due to practical reasons, the sockets in the Teknik room and the Pentry are only connected to the high voltage bus. However, the low power demand appliances connected to the high voltage bus will need a DC/DC converter at the load level.

Table 3.6: High Power Sockets. First floor.

Room	Socket	Load	Max power [W]
1. Vindfång + Balkong	1.1	VC	1100
2. Entré	2.1	VC	1100
3. KLK1	3.1	VC	1100
4. Teknik	4.1	HP	2400
	4.2	WM	2300
	4.3	D	2200
	4.4	VC	1100
	4.5	FTX	900
	4.6	CP	40
	4.7	0	0
	4.8	0	0
	4.9	0	0
	4.10	0	0
	4.11	0	0
	4.12	0	0
	4.13	0	0
5. Vardagsrum	5.1	VC	1100
6. Pentry	4.1	F	160
	4.2	Stv	7200
	4.3	MO	900
	4.4	DW	2040
	4.5	0	0
	4.6	CH	70
	4.7	M	1400
	4.8	0	0
7. Uterum	7.1	VC	1100
8. HWC	8.1	HD	2060

Table 3.7: High Power Sockets. Second floor.

Room	Socket	Load	Max power [W]
9. Stairs + Entré	9.1	VC	1100
10. Badrum	10.1	HD	2060
11. Sovrum1	11.1	VC	1100
12. Allrum	12.1	VC	1100
13. Sovrum2	13.1	VC	1100
14. Sovrum3	14.1	VC	1100

3.3.2.4 Small appliances

This group of loads include the remaining appliances and they are shown in tables 3.8 and 3.9. Notice that four extension cods have been considered, as they are regularly used in households, plugged in sockets 11.2, 12.2, 13.2, and 14.2.

Table 3.8: Low Power Sockets. First Floor.

Room	Socket	Load	Max power [W]
1. Vindfång	1.1 1.2	0 0	0 0
2. Entré	2.1 2.2 2.3 2.4	0 0 0 0	0 0 0 0
3. KLK1	-	-	-
4. Teknik	-	-	-
5. Vardagsrum	5.1 5.2 5.3 5.4 5.5	TV R L L L	90 12 10 10 10
6. Pentry	-	-	-
7. Uterum	7.1 7.2	0 0	0 0
8. HWC	9.1	0	0

Table 3.9: Low Power Sockets. First Floor.

Room	Socket	Load	Max power [W]
9. Stair + Entré	-	-	-
10. Badrum	-	-	-
11. Sovrum 1	11.1	L	10
	11.2	L + PC + Ph	93
	11.3	L	10
	11.4	0	0
12. Allrum	12.1	VGC	130
	12.2	TV + L + L	110
13. Sovrum 2	13.1	0	0
	13.2	L + PC + Ph	93
	13.3	L	10
	13.4	0	0
14. Sovrum 3	14.1	0	0
	14.2	L + PC + Ph	93
	14.3	L	10
	14.4	0	0

3.3.3 Load Profiles

As the Research Villa is full of sensors, the intention was to use data from the actual measurements reported. However, the only data that could be used was the heat pump and the ventilation system's profiles.

Moreover, some tests had been carried out during the measurements, so the heat pump profile has been adapted to a more logical power demand depending on the seasons. However, the ventilation system's profile considered only takes into account the data within its power range: 0-180 W. As it is a small load, its effect on the total demand is not significant.

The circulation pump's profile considered is the same as the one for the heat pump, but in its range of power: from 3 to 40 W.

Figures 3.5, 3.6 and 3.7 show the lowpass-filtered load profiles considered for the heat pump, ventilation system and circulation pump.

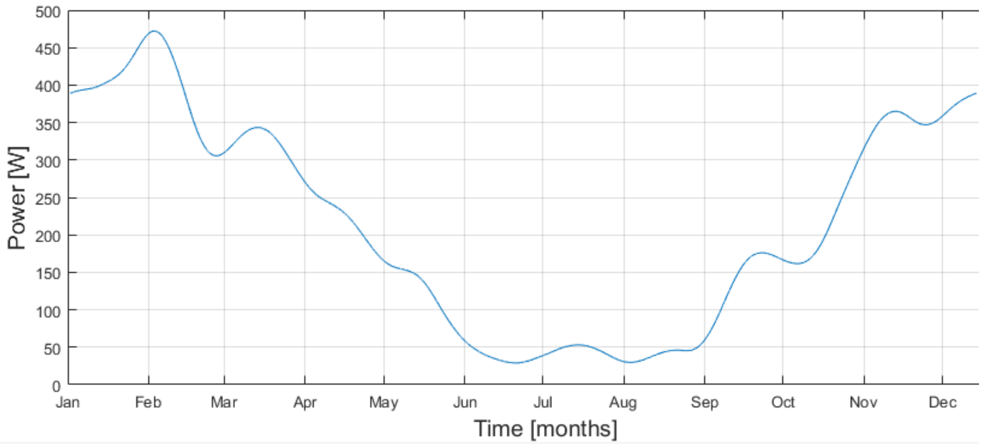


Figure 3.5: Heat Pump Profile

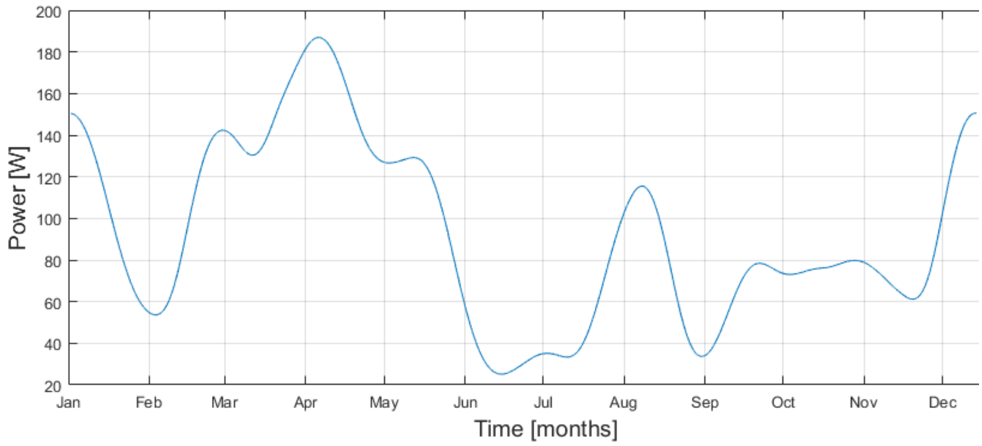


Figure 3.6: Ventilation System Profile

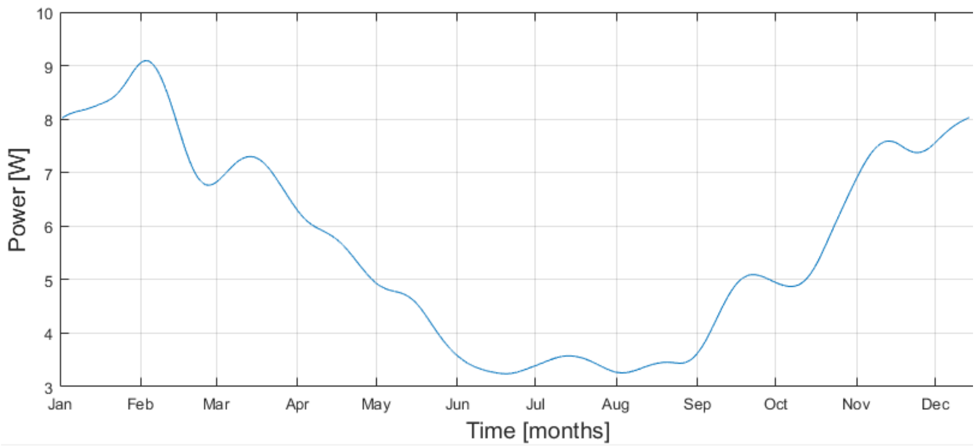


Figure 3.7: Circulation Pump Profile

The remaining load profiles have been estimated according to what an average four-member family would typically consume in a city like Borås, as shown in figure 3.8, where the lighting profile has a strong dependence on the seasons. In figure some of the load profiles are shown.

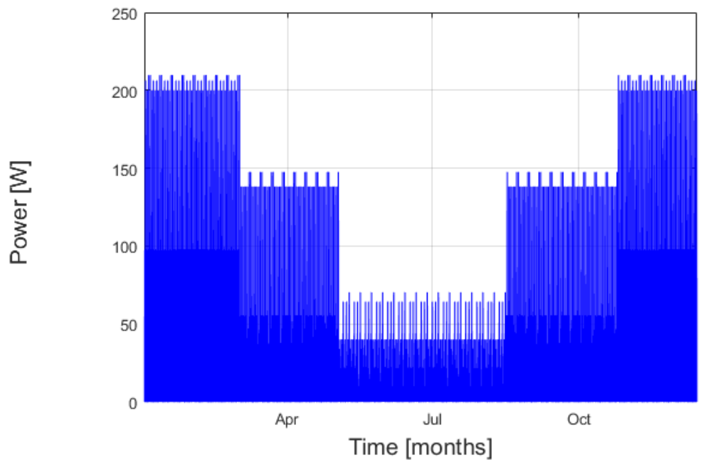
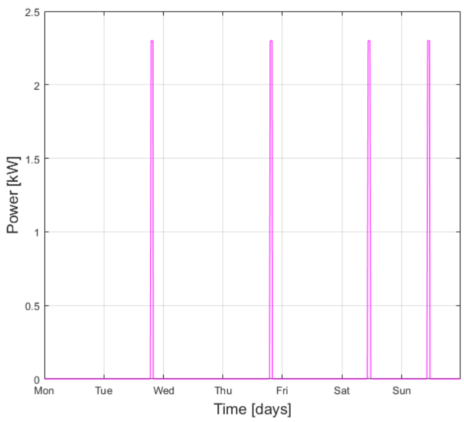
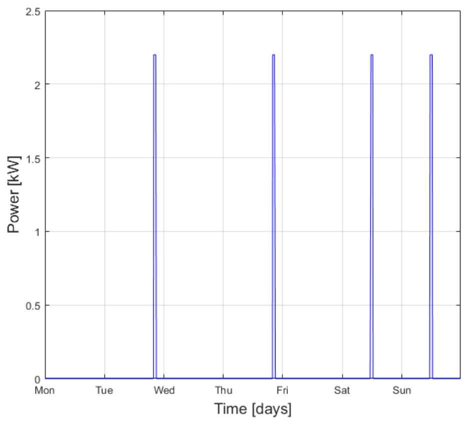


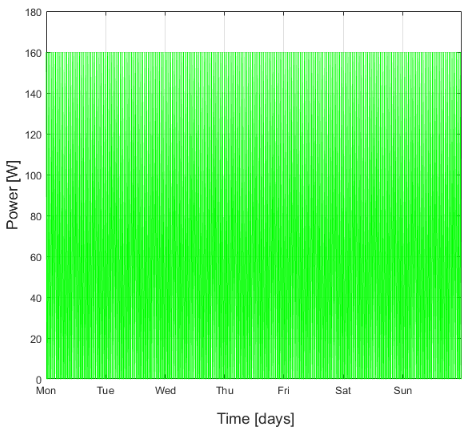
Figure 3.8: Lighting Profile



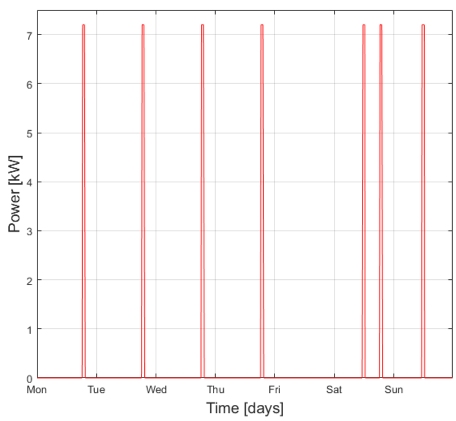
(a) Washing Machine



(b) Clothes Dryer



(c) Fridge



(d) Stove

Figure 3.9: Load Profiles

3.4 Rectifiers and DC/DC converters

3.4.1 Rectifiers

A rectifier is an electric device that converts alternating current (AC) to direct current (DC), and they are required when the electrical distribution system in on AC and the loads run on DC.

The structure of a low-power rectifier is shown in figure 3.10, and the output voltage is 320 VDC. This rectifier is considered for loads with a power demand lower than 50 W.

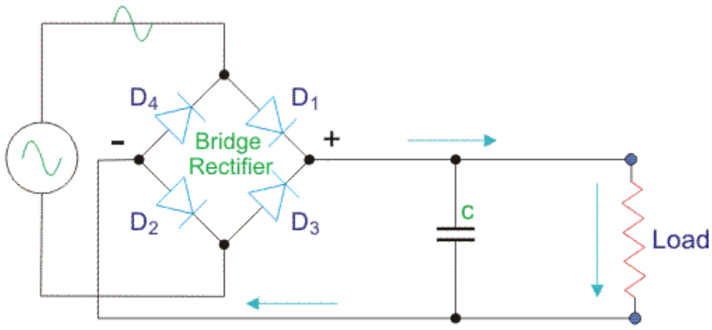


Figure 3.10: Low-power rectifier, [26]

However, for loads with a power demand higher than 50 W, a boost power factor correction converter (PFC) is required in order to make the input current sinusoidal and in phase with the input voltage. The structure of a high-power rectifier is shown in figure 3.11, and its output voltage is 380 VDC.

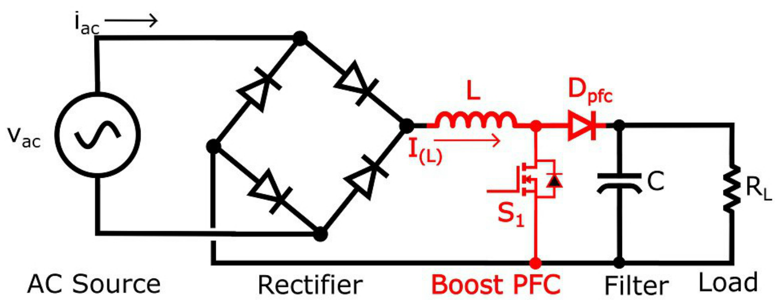


Figure 3.11: Power Factor Corrector converter, [27]

Therefore, in the model developed in this work, rectifiers have been used only in the first scenario studied, which is the present systems of the house: 230 V AC. As all the loads are considered to run on DC, there are rectifiers in all of them. Only the purely resistive ones, as mentioned in 3.3.2.2, do not need rectifiers as they can run both on AC and DC.

The efficiency values considered in this model are shown in table 3.10.

Table 3.10: Rectifier efficiency values

Loads	Power [W]	Rectifier efficiency [%]
Small	< 50	97
Medium	50-400	95
Large	> 400	98

3.4.2 DC/DC converters

DC/DC converters are electric devices that convert the voltage level from a DC source to a different voltage level. They can either provide a higher voltage level (boost or step up converters), or a lower one (bust or step down converters). In these model only step down converters are being used, and an efficiency of 88% is considered.

Figure 3.12 shows the structure of a buck converter. Also, when conversion ratios are higher than 60 V, a full-bridge converter with a transformer is required.

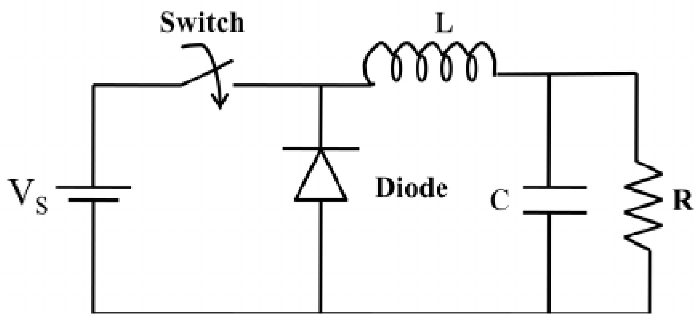


Figure 3.12: Buck Converter, [28]

3.5 Sizing of the cables

The cables are chosen according to the IEC 60228's international standard on conductors of insulated cables. The cross section of the cable required depends on maximum current that they can withstand, as shown in table 3.11.

Table 3.11: International standard wire sizes (IEC 60228)

Max current [A]	**Cross section** [mm^2]
6	0.75
10	1.5
16	2.5
20	4
25	6
34	10
45	16

3.6 Types of Losses

There are three types of loads considered: rectification losses, when converting AC to DC; conversion losses, when converting the voltage level in DC; and conduction losses, due to the Joule effect. In figures 3.1, 3.2, 3.3 and 3.4, the four scenarios studied are shown:

- Scenario 1 shows the present distribution system: 230 V AC. Therefore there is only one voltage bus, which means that the conduction losses will happen at 230 V AC. Then, all the loads except for the purely resistive ones need rectifiers, which efficiency value depends on the power demand of the load, as explained in 3.4.1. Afterwards, the loads with a power demand lower than 400 W need a DC/DC converter in order to adapt the voltage level to the one required by the load.

- Scenario 2 shows a distribution system with one voltage bus of 380 V DC. In this case, the conduction losses will happen at this voltage level. After that, only the loads with a power demand lower than 400 W will require a DC/DC converter.

- Scenario 3 shows a distribution system with two voltage buses: 380 V DC and 54 V DC. Therefore, there are conduction losses at both of these voltage levels: loads with a power demand higher than 400 W will be able to run at 380 V DC. However, the second bus is extracted from the first one, through a DC/DC converter. Loads with a power demand between 50 and 400 W can run at 54 V DC whereas loads with a lower power demand need another conversion step.

- Scenario 4 also shows a distribution system with two voltage buses: 380 V DC and 20 V DC. In this case, the are conduction losses at both of these voltage levels: loads with a power demand higher than 100 W will be connected to the high voltage bus, and only the ones with a power demand lower than 400 W require a DC/DC converter. The low voltage bus is extracted from the high voltage one, so a DC/DC converter is required, but then the loads connected to this voltage bus can be run directly at 20 V DC.

3.6.1 Rectification losses

The power lost in rectification depends on the efficiency of the rectifier, as shown in 3.2.

$$\eta_{AC/DC} = \frac{P_{AC/DCoutput}}{P_{AC/DCinput}} \tag{3.1}$$

$$P_{AC/DCLosses} = P_{AC/DCinput} - P_{AC/DCoutput} = \frac{1 - \eta_{AC/DC}}{\eta_{AC/DC}} P_{AC/DCoutput} \tag{3.2}$$

As mentioned in section 3.4.1, these losses will only happen in the AC scenario.

3.6.2 Conversion losses

The power loss in conversion depends on the efficiency of the DC/DC converters, as shown in 3.4.

$$\eta_{DC/DC} = \frac{P_{DC/DCoutput}}{P_{DC/DCinput}} \tag{3.3}$$

$$P_{DC/DCLosses} = P_{DC/DCinput} - P_{DC/DCoutput} = \frac{1 - \eta_{DC/DC}}{\eta_{DC/DC}} P_{DC/DCoutput} \tag{3.4}$$

As mentioned in section 3.4.2, these losses will depend on the distribution system studied.

3.6.3 Conduction losses

Joule Effect is the dissipation of power in a resistance due to an electrical current, which generates heat. The power lost in conduction is calculated as follows:

$$Pconduction = RI^2 \tag{3.5}$$

The resistance is calculated depending on the cross section of the cables, as follows:

$$R = \rho \frac{l}{s} \tag{3.6}$$

where ρ is the resistivity value of the copper, which is 1.72e-8 [Ωm] at 20ºC; l is the length of the cable; and s is its cross section.

In scenario 1 (AC case), in order to consider the extra losses due to the alternating nature of the current, such as the skin effect, a coefficient "c" is added in the resistance, with a value of 1.02, obtained by differential equations and Bessel functions, [25]. This phenomenon is characterized by the nonuniform distribution of the current due to the frecquency of the AC voltage, which produces the reduction of the effective cross-section area used by the current.

The current is calculated as shown in 3.7, where the power depends on the scenario, and the voltage is the voltage level of the bus, and it is the same for both AC and DC systems, as it is said in IEC 60364-5-523:1999 standard.

$$I = \frac{P}{V} \tag{3.7}$$

3.7 Cost calculations

In order to carry out the life cycle cost analysis, the prices for the cables depending on their cross section was required. Table 3.12 shows the prices by METSEC.

Table 3.12: Prices of cables

Cross section [mm^2]	**Price** [SEK/m]
0.75	1.4904
1.5	2.2248
2.5	3.6288
4	5.769
6	8.55
10	14.8878
16	23.7888

Therefore, once the cross section required is calculated, we can find the corresponding price in table 3.12 and if we multiply it by its feeder length, we get the price of the whole cable. Adding the prices of all the cables we get the price of the whole installation, as shown in 3.8.

$$CableCost = \sum_{i=1}^{N} Price_i * FeederLength_i \tag{3.8}$$

4

Modelling and Simulations

The model of the distribution system of a generic household based on the Research Villa has been made using Matlab. The aim was to have a realistic model to run simulations of different voltage levels and study the losses in each case and as well as the cost of the installation.

The model depends on the scenario we want to simulate. There is a main script and four functions, one for each scenario considered. The structure of the main script is as follows:

1. Choice of the scenario to simulate
2. Loading of the data
3. Sizing of cables
4. Loading of the load profiles
5. Calculation of the power and energy demand
6. Call to the scenario chosen function
7. Results

The simulation time is 347 days, which is the time of the data provided by the Research Villa. There are 4 measurements in each hour, which makes a total of 33312 measurements in the simulation time. Actually, from the Research Villa only the data from the heat pump and the ventilation system could be used, as the rest of the loads were not measured or the measurements would not match the way required in this model.

4.1 Main script

4.1.1 Choice of the scenario to simulate

The Main script starts with a request to choose the scenario we want to simulate, as shown in figure 4.1.

```
>> Matlab Model of the Distribution System of a generic household based on the Research Villa <<

This program can run the following 4 scenarios:
 Scenario 1: 230 VAC
 Scenario 2: 380 VDC
 Scenario 3: 380 & 54 VDC
 Scenario 4: 380 & 20 VDC

Please, enter the number of the scenario you would like to run:
```

Figure 4.1: Input request

If scenario 1 is chosen, then the variable c for coefficient gets the value of 1.02 in order to consider the skin effect losses due to the alternating nature of AC. Else, that variable c gets the value of 1. This coefficient will be used when calculating the resistance of the cables.

4.1.2 Loading of data

First of all, the time vector is loaded: 33312 values from 01/01/2016 00:00 h until 12/12/16 23:59 h, which is the period of time when we have measurements from the heat pump and the ventilation system. Also, the value of the resistance of copper, in order to calculate the conduction losses, is added in this section. Then, a vector with the number of lights that are turned on/off when using each switch is declared here.

After that, the power demand of each load is declared: lighting, large loads, small loads and purely resisitive loads. The total demand of those loads that have a resistive part and an electric motor (washing machine, dishwasher, clothes dryer and hairdryer) is calculated afterwards.

Finally, the efficiency values considered for each rectifier and for the converters are declared in this section.

4.1.3 Sizing of cables

An Excel file called "LoadProfiles" includes some of the data that is required in order to run the program. The first sheet of this Excel file is called "Feeder lengths" and includes the feeder lengths of the cables. It includes five vectors with different lengths, depending on the number of cables of each type, as shown in the table 4.1. The lengths of the cables are expressed in meters and were taken from the plans of the Research Villa.

Therefore, the lengths of all the cables of the house are loaded and kept in vectors named "fl_x", where x is a number from 1 to 5, depending on the group of the cables. Also, the value of the power demand of each load is added here: each load will be connected to one specific socket or light point.

Table 4.1: Groups of cables

Group	**Number of cables**
1. Lighting cables to nodes	13
2. Lighting cables node-light	24
3. Cables to resistive loads	5
4. Cables to high power sockets	33
5. Cables to low power sockets	28

4.1.4 Loading of the load profiles

The load profiles are located in the Excel file called "LoadProfiles", in sheets 2-6 as shown in the table 4.2. The data from the measurements of the Research Villa were kept in a vector of 33312 values, so all the load profiles have been kept the same way.

Table 4.2: Excel file

Sheet	**Loads**
1. Lighting	24: one for each switch
2. Resistive	5: one for each resistive load
3. Large	33: one for each high power socket
4. Small	28: one for each low power socket
5. EC	12: one for each socket of the 4 extension cods

This load profiles are given in a digital format: 1 for on and 0 for off, except for the heat pump, ventilation system and circulation pump, which take values from 0 to 1 depending on the percentage of their maximum power demand required. Afterwards, each load gets its power demand by multiplying the load profiles loaded and the value of the power demand of each load.

As for the extension cods, the total power demand of the loads connected to them is considered as one load connected to the socket where the extension cod is connected.

4.1.5 Calculation of the power and energy demand

The power demand of each type of load is calculated adding the power demand of each load in each instant. Afterwards, the total power demand is calculated adding the total power demand of each type of load.

As for the energy, it is calculated using the Matlab function "trapz".

4.1.6 Call to the function for the scenario chosen

Depending on the scenario chosen, a different function will be called. The functions developed are explained below. In order to follow the explanation easily, the reader may look at figures 3.1, 3.2, 3.3 and 3.4.

4.1.6.1 Scenario 1: 230 VAC

In this scenario, the loads with a power demand lower than 400 W need a DC/DC converter. Therefore, the input power to the DC/DC converters is calculated using 3.3. Then, the losses as calculated as shown in 3.4.

Once the input power of the DC/DC converters is calculated, the next step is calculating the rectification losses. Therefore, the output of the rectifier is the same as the input of the DC/DC converter. Following the same procedure as for the DC/DC converter losses, the input power of the rectifier is calculated using 3.1 and the rectification losses are calculated as shown in 3.2. Notice that all the loads except for the resistive ones need a rectifier in order to run on DC.

The input power of the rectifiers is the power that needs to reach the rectifiers after the conduction through the cables. Therefore, in order to calculate the conduction losses, the current must be known. The current required by each load is calculated dividing its power (including the rectification and conversion losses) by the voltage of the bus where it is connected. Once all the currents are calculated, the current through each cable is calculated: the layout of the loads corresponds with the one in the plans of the Research Villa.

Afterwards, the cross section of each cable can be chosen, as it depends on the maximum current that the cable will carry. Then, the resistance is calculated as shown in 3.6. Finally, the conduction losses can be calculated as shown in 3.5.

The total losses are calculated adding the losses in conversion, rectification and conduction. The energy lost is calculated once again using the "trapz" Matlab function. The total consumption is, therefore, the power demand plus the power losses.

4.1.6.2 Scenario 2: 380 VDC

In this scenario, the first step is the same as in scenario 1: loads with a power demand lower than 400 W need a DC/DC converter.

Then, as there are no rectification losses, the next step is calculating the currents, resistances and conduction losses, as explained in the previous scenario.

Finally, the total power and energy consumption and losses are calculated.

4.1.6.3 Scenario 3: 380&54 VDC

Once again, the first step is calculating the DC/DC conversion losses at the loads' level. In this case, there are two buses in the distribution system. Therefore, both the loads with a power demand lower than 400 W connected to the high voltage bus, and the ones with a power demand lower than 100 W connected to the low voltage bus, need a DC/DC converter. The losses are calculated as explained in section 3.6.

Then, there are no rectification losses as the distribution voltage is on DC, so the next step is calculating the currents, resistances and conduction losses, taking into account both voltage levels and the loads connected to them.

Afterwards, the DC/DC conversion from 380 VDC to 54 VDC also adds losses to the system. The way to calculate them is exactly the same as explained before, but in this case the output of the DC/DC converter is the addition of the power demand plus the losses in conversion and conduction in the low voltage bus.

The conduction losses include the ones in both voltage buses. Also, the conversion losses include the losses in both conversion stages.

4.1.6.4 Scenario 4: 380&20 VDC

In this case, only the loads with a power demand lower than 400 W connected to the high voltage bus will require a DC/DC converter at the loads' level.

Once again, there are no rectification losses, so the next step is the calculation of the currents, resistance and conduction losses, in both buses, taking into account the voltage levels of the distribution system.

As in the previous scenario explained, there is a second conversion stage, from the 380 VDC bus to the low voltage one. The conversion losses are calculated the same way as explained before, and added to the conversion losses at the load's level.

Finally, the conduction losses are calculated, including the ones in both voltage buses.

4.1.7 Results

Screenshots of the results are shown in the Appendix B of this report.

5

Results

5.1 Demand

The same demand is considered in the four scenarios. After running the simulations, the results obtained are shown in table 5.1.

Table 5.1: Demand

Max lighting power demand	209.8 W
Max purely resistive loads power demand	3.8 kW
Max large appliances power demand	13.8 kW
Max small appliances power demand	312 W
Max total power demand	13.9 kW
Lighting energy demand	112.3 kWh
Purely resistive loads energy demand	509.8 kWh
Large appliances energy demand	7971.1 kWh
Small appliances energy demand	411.1 kWh
HVAC demand	2595.2 kWh
Total energy demand	9004.4 kWh

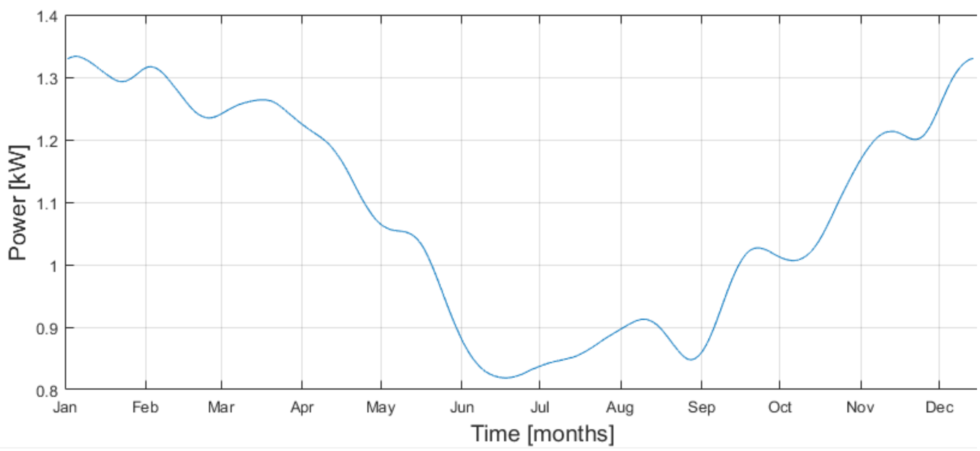


Figure 5.1: Power demand

Figure 5.1 shows the lowpass-filtered total power demand.

5.2 Losses

The results obtained after the simulations are shown in figure 5.2. The total demand is the same in the four scenarios, so scenario 2 is the one that has the less losses (4.44%) and scenario 4 has the most losses (9.20%). These results make sense, as the higher the voltage level of the distribution system, the less conduction losses. According to these results, scenarios 2 and 3 are more economic solutions than scenario 1, but in scenario 3 the losses are greater than in scenario 1.

		230 VAC	380 VDC	380&54 VDC	380&20 VDC
Conduction losses	kWh	158,1	109,1	203,3	475,1
	%	1,64	1,16	2,09	4,79
Rectification losses	kWh	156,7	0	0	0
	%	1,6	0,0	0,0	0,0
Conversion losses	kWh	305	305	497	437,4
	%	3,2	3,2	5,1	4,4
Total losses	kWh	619,8	414,1	700,3	912,5
	%	6,44	4,40	7,22	9,20
Total demand	kWh	9004,4	9004,4	9004,4	9004,4
	%	93,56	95,60	92,78	90,80
Total consumption	kWh	9624	9419	9705	9917
Total cost of cables	SEK	13102	11602	11767	13610

Figure 5.2: Losses

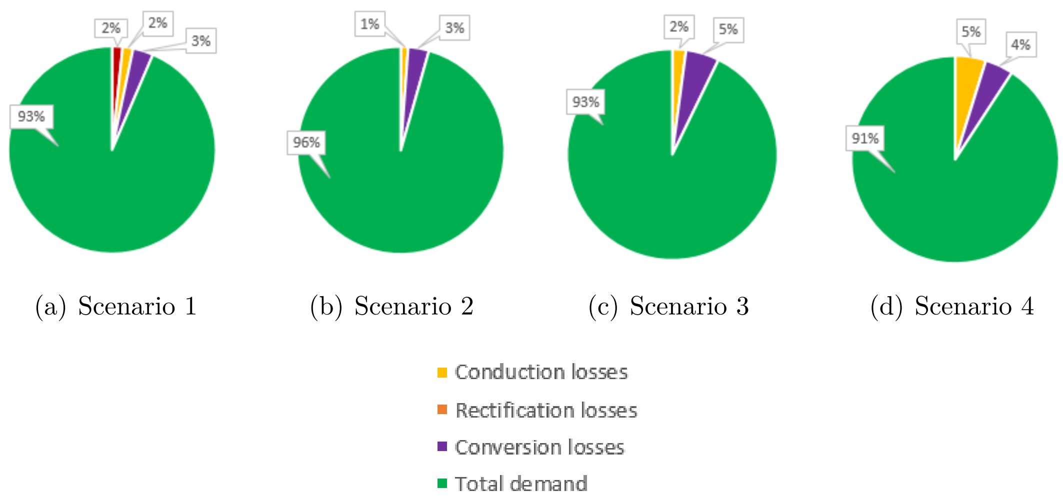


Figure 5.3: Total consumption

6

Life Cycle Cost

In this chapter, the profitability of choosing thicker (and, therefore, costlier) cables for the distribution system in order to lower the conduction losses, is studied. As shown in 3.6, the resistance is inversely proportional to the cross section of the cable: the thicker a cable is, the lower its resistance will be. Therefore, choosing thicker cables will lower the conduction losses. However, thicker cables are costlier, so it seems interesting to know whether a higher investment in the cables of the installation will be profitable in the long run.

In order to compare different options and find the most profitable one, the net present value (NPV) of each case should be calculated. Net Present Value (NPV) is the value of all future cash flows over the entire life of an investment discounted to the present. Considering that the electrical installation will last for 30 years and being the prices of energy in the following years the ones predicted by Statista and shown in table 6.1, the NPV is calculated according to 6.1.

Table 6.1: Price of electricity

Years	**Price [SEK/kWh]**
2018-2022	1.940
2023-2027	1.970
2028-2032	2.012
2033-2037	2.070
2038-2042	2.040
2043-2047	2.000

$$NPV = -Investment + \sum_{t=1}^{30} \frac{-EnergyLosses * price(t)}{(1+r)^t} \tag{6.1}$$

In 6.1, r is the discount rate and the calculations have been made choosing the legal money discount rate, which is 3%; and also 5%, considering that this parameter is going to increase in the following years. The results are shown in table 6.3.

In table 6.2, the lengths of the cables of each cross section for the studied cases are shown.

Table 6.2: Lengths [m] of the cables

Cross sections [mm2]		0.75	1.50	2.50	4.00	6.00	10.0
230 VAC	**Base case**	7060	95	0	25	0	153
380 VDC	**Case 1**	7155	25	0	153	0	0
	Case 2	7155	25	0	0	153	0
	Case 3	7155	0	25	0	153	0
	Case 4	6190	990	0	0	153	0
380&54 VDC	**Case 1**	6931	249	0	153	0	0
	Case 2	6931	249	0	0	153	0
	Case 3	6931	224	25	0	153	0
	Case 4	6190	990	0	0	153	0
380&20 VDC	**Case 1**	6551	165	240	221	156	0
	Case 2	6551	25	380	68	309	0
	Case 3	6551	25	240	208	309	0
	Case 4	6090	626	240	68	309	0

In this study, the value of NPV in all the cases is negative because both the inversion and the losses are negative flows of cash. Therefore, the lower the absolute value of NPV, the most economic the case in the long run. In fact, those ones with a lower absolute value of NPV than 230 VAC's case are more profitable that the present situation. Looking at the results in table 6.3, only scenario 2 (380 VDC) is more profitable than scenario 1, and the most profitable case would be case 2.

Table 6.3: NPV for 30 years

Scenario	Case	Investment in cables [SEK]	Total losses [kWh]	NPV (r=3%)	NPV (r=5%)
230 VAC	Base	13102	619.8	-37371	-32084
380 VDC	1	11602	414.4	-27816	-24284
	2	12028	386.8	-27173	-23874
	3	12063	386.3	-27189	-23894
	4	12736	386.2	-27858	-24564
380&54 VDC	1	11767	700.3	-39188	-33215
	2	12192	673	-38544	-32804
	3	12227	672.5	-38559	-32823
	4	12736	653.6	-38328	-32753
380&20 VDC	1	13610	912.5	-49340	-41557
	2	14232	856.3	-47761	-40457
	3	14532	849.8	-47806	-40558
	4	14374	876.7	-48702	-41224

7

Discussion

7.1 Social, ethical and sustainable aspects of LVDC

The main advantage of DC when compared to AC is the loss reduction, specially when both generation and consumption are made using DC. Therefore, a DC distribution system is more efficient than an AC one, which implies that there is a better usage of resources: less energy is consumed and therefore less is the cost of the energy consumed. Specially with today's trends, such as distributed generation and integration of renewable energy sources in the electrical system, LVDC avoids the rectification losses. This is a win-win situation: consuming less resources is good for the environment as we save natural resources and reduce pollution, and the energy bill is less every month.

Moreover, LVDC is an opportunity for electricity access in developing countries. Still, more than 1.2 billion people in the world lack this basic necessity. However, the recent technological advances that allow the reduction of the cost of solar PV panels, the development of LED lighting and the availability of high-performance batteries, enable the development of local power supply installations, isolated from the main grid. The key success factors of LVDC are the low initial investment required and the long term maintainability using locally source components, [12], [13].

Research is still required in order to determine the hazards on the human body, as the effect caused by DC is different from AC; overvoltage protection, fault detection, and so on. Once there are some conclusions, standarization will be possible, and then one more step towards sustainable development could be taken.

Also, as mentioned before, LVDC systems make the most sense when there is distributed generation from renewable sources, as they provide power in the DC form. The more energy production from renewable sources, as well as the less that comes from conventional energy sources, a reduction in the carbon footprint follows, and a step forward in terms of sustainability.

7.2 Further work

Nowadays many companies are considering running their products on DC. This fact along with the increase in the usage of electronic devices, which are also powered with DC, make it necessary to study the voltage levels required in order to establish the optimum voltage level in the distribution system of a conventional household, or the DC/DC converters that will be required.

Moreover, the load profiles used in this work consider a constant power consumption during the period of time when the appliance is running (except for the data that comes from actual measurements). Therefore, some research in order to estimate more accurate load profiles would be required.

Once that the voltage levels of the appliances are known, the DC/DC converters can be chosen accordingly, and their efficiency and cost could be studied.

In addition, a more detailed life cycle cost analysis could be carried out, including the prices of protections, sockets, DC/DC converters, and so on.

Finally, the source of power could be included in the model: PV production, battery storage system, grid, control algorithm and response of the system could be simulated using the model developed in this work.

8

Conclusion

The first conclusion of this work is that the rectification losses in scenario 1 are 1,6%, whereas the conduction and conversion losses in scenarios with two voltage levels are higher than in the first case. Therefore, in terms of efficiency, two voltage levels in the distribution system of the house is not a feasible option. This along with the fact that there are needs for high power sockets in all the rooms (in order to plug the vaccum cleaner, for instance), are the main disadvantages of having a two-voltage-level DC distribution system. However, the major advantage of a two-voltage level DC distribution system is safety, as lower voltage levels reduce the danger of electrical shock.

Another conclusion that can be extracted from this work is the importance of the Life Cycle Cost Analysis: scenario 3's initial investment was more economic than the base case, but in the long term it turned out to be more expensive.

Finally, a single voltage level at 380 VDC with one-step up thicker cable for the stove seems to be the most profitable solution, providing savings of 8210 SEK (r=5%) after the lifetime of the installation.

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A

Appendix 1: Plans

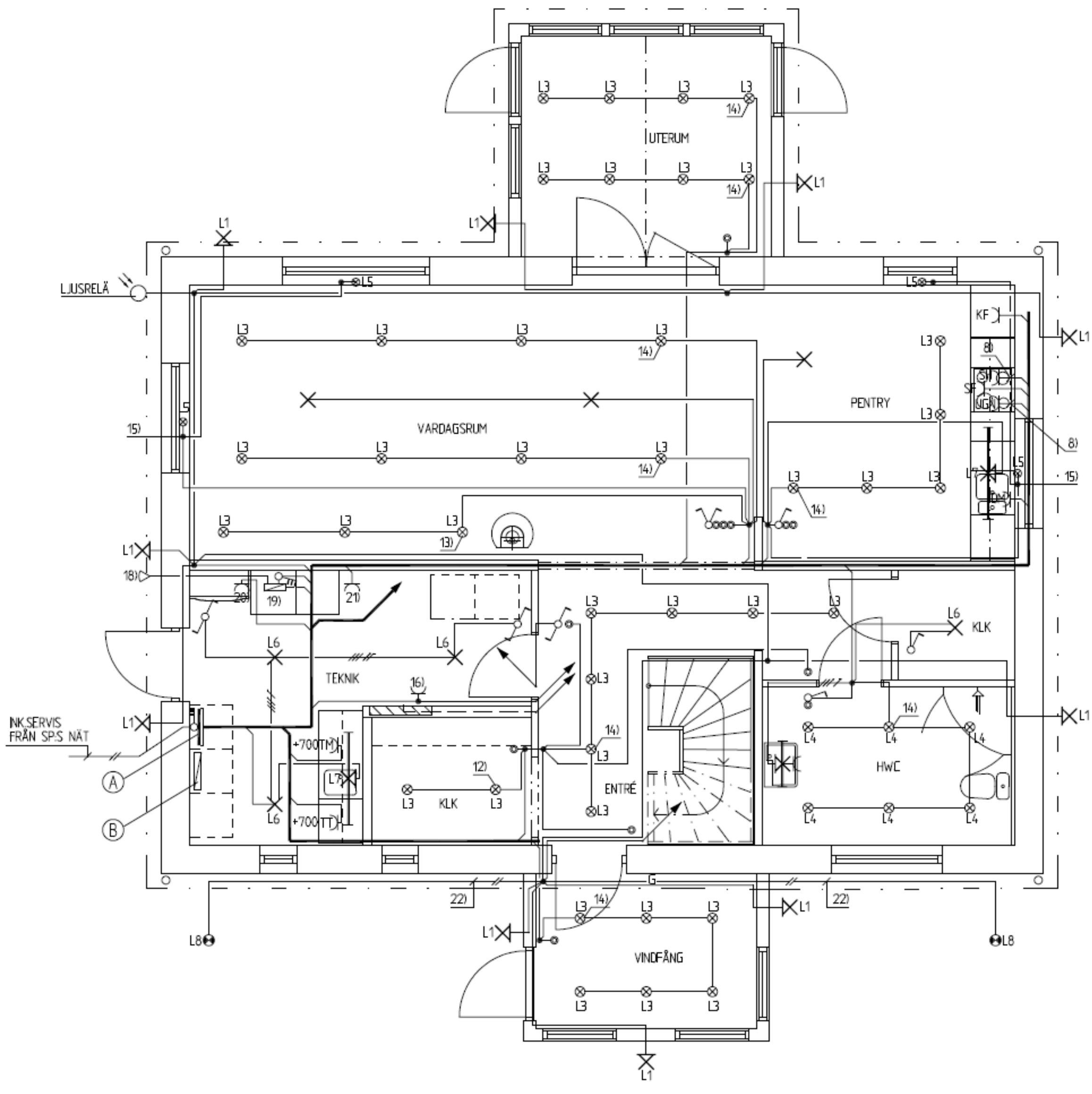

Figure A.1: Lighting system, first floor.

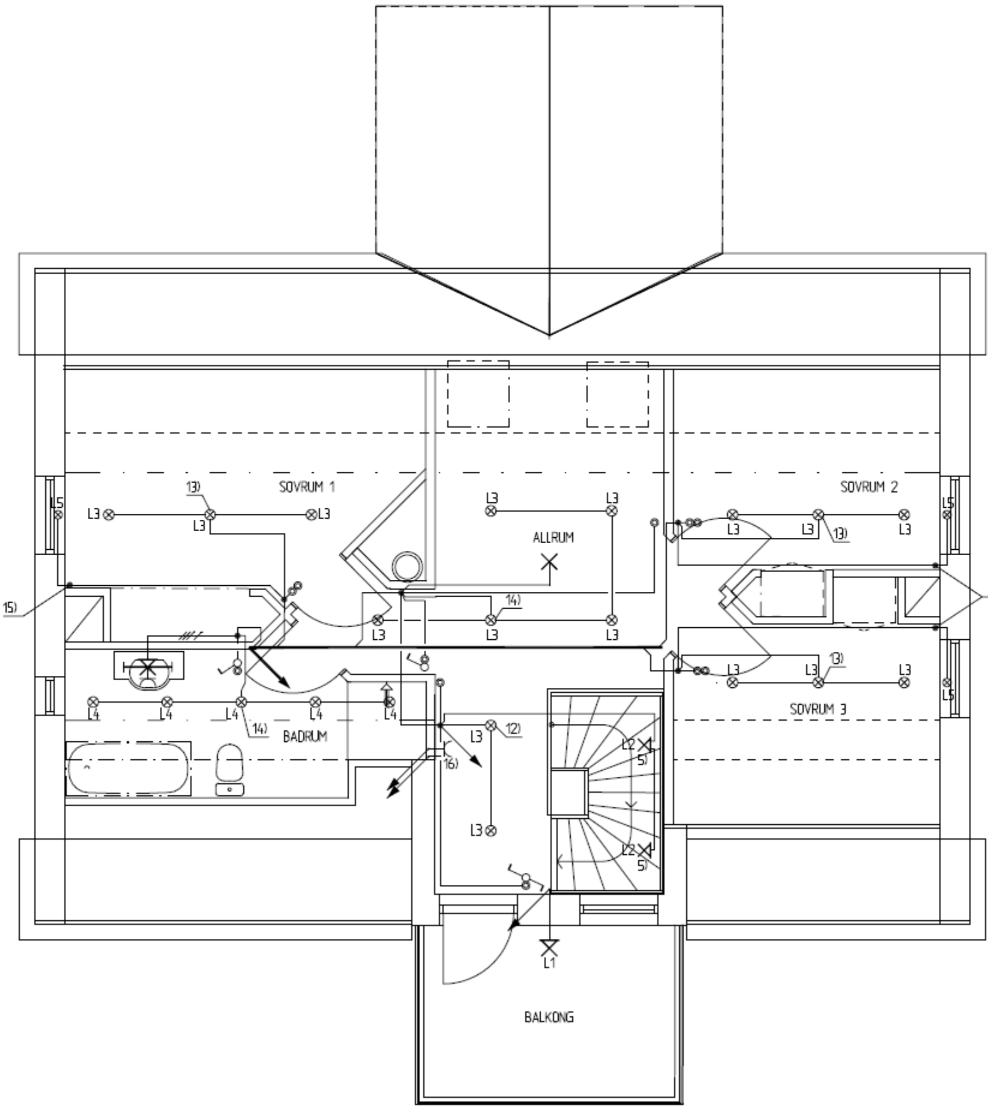

Figure A.2: Lighting system, second floor.

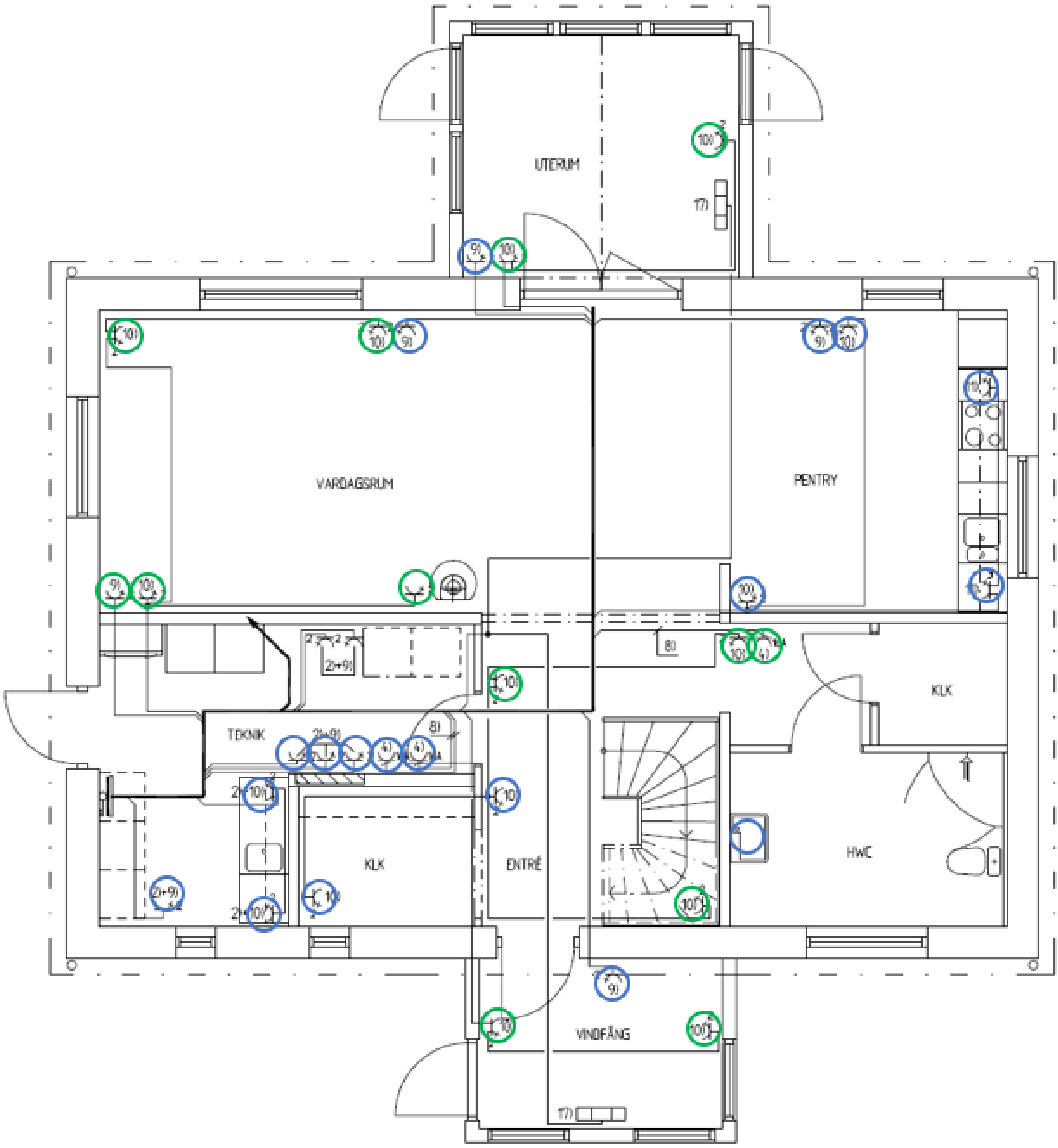

Figure A.3: Sockets, first floor.

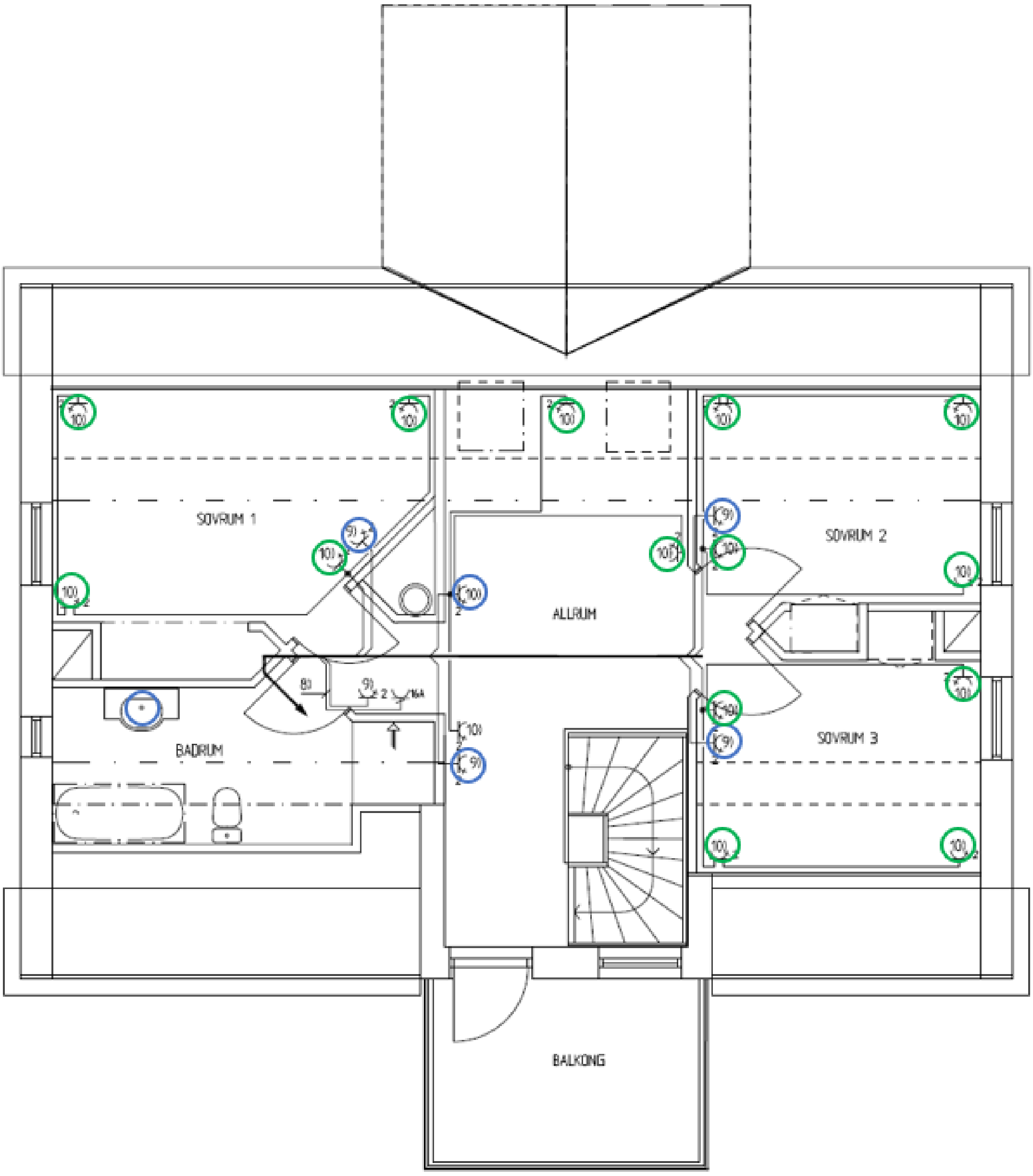

Figure A.4: Sockets, second floor.

B

Appendix 2: Screenshots of the simulations

```
>> Matlab Model of the Distribution System of a generic household based on the Research Villa <<

This program can run the following 4 scenarios:
 Scenario 1: 230 VAC
 Scenario 2: 380 VDC
 Scenario 3: 380 & 54 VDC
 Scenario 4: 380 & 20 VDC

Please, enter the number of the scenario you would like to run:

1

---------------------- AC Distribution System ----------------------

Scenario 1: Base case: 230 VAC

Running simulation.......

 1. Loading data.............................................Done.
 2. Loading lengths of cables................................Done.
 3. Loading loads profiles...................................Done.
 4. Calculating Demand.......................................Done.
 5. Calculating conversion losses at loads level.............Done.
 6. Calculating rectification losses.........................Done.
 7. Loading loads layout.....................................Done.
 8. Calculating cables thickness.............................Done.
 9. Calculating conduction losses............................Done.
10. RESULTS:

MAX POWER:
Lighting power demand:                     209.8  W
Purely resistive loads power demand:         3.8 kW
Large appliances power demand:              13.8 kW
Small appliances power demand:             312.0  W
Total power demand:                         13.9 kW
Total power losses:                          0.7 kW
Total power consumption:                    14.6 kW

ENERGY
Lighting demand:                           112.3 kWh
Purely resistive loads demand:             509.8 kWh
Large appliances demand:                  7971.1 kWh
Small appliances demand:                   411.1 kWh
HVAC demand:                              2595.2 kWh
Total demand:                             9004.4 kWh
Conduction losses:                         158.1 kWh (25.5 %)
Rectification losses:                      156.7 kWh (25.3 %)
Conversion losses:                         305.0 kWh (49.2 %)
Total losses:                              619.8 kWh ( 6.4 %)
Total cosumption:                         9624.2 kWh

COST
Total cost of the cables:                  13102 SEK
```

Figure B.1: Results scenario 1

```
>> Matlab Model of the Distribution System of a generic household based on the Research Villa <<

This program can run the following 4 scenarios:
 Scenario 1: 230 VAC
 Scenario 2: 380 VDC
 Scenario 3: 380 & 54 VDC
 Scenario 4: 380 & 20 VDC

Please, enter the number of the scenario you would like to run:

2

----------------------- DC Distribution System -----------------------

Scenario 2: Single DC Voltage level: 380 VDC

Running simulation.......

 1. Loading data.............................................Done.
 2. Loading lengths of cables................................Done.
 3. Loading loads profiles...................................Done.
 4. Calculating Demand.......................................Done.
 5. Calculating conversion losses at loads level.............Done.
 6. Calculating rectification losses.........................Done.
 7. Loading loads layout.....................................Done.
 8. Calculating cables thickness.............................Done.
 9. Calculating conduction losses............................Done.
10. RESULTS:

MAX POWER:
Lighting power demand:                    209.8  W
Purely resistive loads power demand:        3.8 kW
Large appliances power demand:             13.8 kW
Small appliances power demand:            312.0  W
Total power demand:                        13.9 kW
Total power losses:                         0.4 kW
Total power consumption:                   14.2 kW

ENERGY
Lighting demand:                          112.3 kWh
Purely resistive loads demand:            509.8 kWh
Large appliances demand:                 7971.1 kWh
Small appliances demand:                  411.1 kWh
HVAC demand:                             2595.2 kWh
Total demand:                            9004.4 kWh
Conduction losses:                        109.1 kWh (26.4 %)
Rectification losses:                       0.0 kWh ( 0.0 %)
Conversion losses:                        305.0 kWh (73.6 %)
Total losses:                             414.2 kWh ( 4.4 %)
Total cosumption:                        9418.5 kWh

COST
Total cost of the cables:                 11602 SEK
```

Figure B.2: Results scenario 2

```
>> Matlab Model of the Distribution System of a generic household based on the Research Villa <<

This program can run the following 4 scenarios:
 Scenario 1: 230 VAC
 Scenario 2: 380 VDC
 Scenario 3: 380 & 54 VDC
 Scenario 4: 380 & 20 VDC

Please, enter the number of the scenario you would like to run:

3

----------------------- DC Distribution System -----------------------

Scenario 3: Two DC Voltage Levels: V1 = 380 VDC & V2 = 54 VDC

Running simulation.......

 1. Loading data..............................................Done.
 2. Loading lengths of cables.................................Done.
 3. Loading loads profiles....................................Done.
 4. Calculating Demand........................................Done.
 5. Calculating conversion losses at loads level..............Done.
 6. Calculating rectification losses..........................Done.
 7. Loading loads layout......................................Done.
 8. Calculating cables thickness..............................Done.
 9. Calculating conduction losses.............................Done.
10. Calculating conversion losses from HV bus to LV bus.......Done.
11. RESULTS:

MAX POWER:
Lighting power demand:                      209.8  W
Purely resistive loads power demand:          3.8 kW
Large appliances power demand:               13.8 kW
Small appliances power demand:              312.0  W
Total power demand:                          13.9 kW
Total power losses:                           0.7 kW
Total power consumption:                     14.3 kW

ENERGY
Lighting demand:                            112.3 kWh
Purely resistive loads demand:              509.8 kWh
Large appliances demand:                   7971.1 kWh
Small appliances demand:                    411.1 kWh
HVAC demand:                               2595.2 kWh
Total demand:                              9004.4 kWh
Conduction losses:                          203.3 kWh (29.0 %)
Rectification losses:                         0.0 kWh ( 0.0 %)
Conversion losses:                          497.0 kWh (71.0 %)
Total losses:                               700.3 kWh ( 7.2 %)
Total cosumption:                          9704.6 kWh

COST
Total cost of the cables:                   11767 SEK
```

Figure B.3: Results scenario 3

```
>> Matlab Model of the Distribution System of a generic household based on the Research Villa <<

This program can run the following 4 scenarios:
 Scenario 1: 230 VAC
 Scenario 2: 380 VDC
 Scenario 3: 380 & 54 VDC
 Scenario 4: 380 & 20 VDC

Please, enter the number of the scenario you would like to run:

4

----------------------- DC Distribution System -----------------------

Scenario 4: Two DC Voltage Levels: V1 = 380 VDC & V2 = 20 VDC

Running simulation.......

 1. Loading data.............................................Done.
 2. Loading lengths of cables................................Done.
 3. Loading loads profiles...................................Done.
 4. Calculating Demand.......................................Done.
 5. Calculating conversion losses at loads level.............Done.
 6. Calculating rectification losses.........................Done.
 7. Loading loads layout.....................................Done.
 8. Calculating cables thickness.............................Done.
 9. Calculating conduction losses............................Done.
10. Calculating conversion losses from HV bus to LV bus.......Done.
11. RESULTS:

MAX POWER:
Lighting power demand:                       209.8  W
Purely resistive loads power demand:           3.8 kW
Large appliances power demand:                13.8 kW
Small appliances power demand:               312.0  W
Total power demand:                           13.9 kW
Total power losses:                            1.0 kW
Total power consumption:                      14.3 kW

ENERGY
Lighting demand:                             112.3 kWh
Purely resistive loads demand:               509.8 kWh
Large appliances demand:                    7971.1 kWh
Small appliances demand:                     411.1 kWh
HVAC demand:                                2595.2 kWh
Total demand:                               9004.4 kWh
Conduction losses:                           475.1 kWh (52.1 %)
Rectification losses:                          0.0 kWh ( 0.0 %)
Conversion losses:                           437.4 kWh (47.9 %)
Total losses:                                912.4 kWh ( 9.2 %)
Total cosumption:                           9916.8 kWh

COST
Total cost of the cables:                    13610 SEK
```

Figure B.4: Results scenario 4