CODEN:LUTEDX/(TEIE-5395)/1-90/(2017)

Industrial Electrical Engineering and Automation

System design of a DC based Micro grid

A comparison study on the Andaman Islands

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A comparison study on the Andaman Islands

A Master's Thesis in Electrical Power systems carried out at
RISE in Gothenburg

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2017

Printed in Sweden
E-huset, Lund, 2017

Abstract

The world today stands at a cross roads when it comes to energy and electrical grids. A large part of the worlds population still lacks access to reliable working electricity 24 hours a day. Much of this is in remote and poor parts of the world. For much of the 20th century large centralized AC grids have been the norm to provide people with electricity. But for remote parts of the world including island communities this have been problematic, because of the difficulty and high cost of extending the main AC grid to them. With the introduction of large amounts of renewable energy into our grids in combination with the increasing use of DC appliances inside our homes, the idea of using DC as the main way for transmission and distribution in the form of isolated microgrids has gained traction.

This thesis as a part of bilateral research project between the Swedish Energy Agency and India's Ministry of New and Renewable Energy, looks at a renewable energy based DC microgrid on the Andaman Islands in India. With the background being an earlier pre study that recommended an island called Rutland Island as a pilot site. With the aim to propose a suitable design for both long term and reliable electrical supply, while at the same time looking at the current state of DC grids and the possible future. This is done by testing two different microgrid designs based on two different scenarios, the current energy consumption of the Rutland community and an average Indian per capita energy consumption.

The thesis concludes that for a DC microgrid of this size, cables are an important aspect, but as a whole including the economic analysis DC/DC converters and batteries are more important, especially if aiming for the future design with Lithium-ion batteries instead of Lead-acid. Both components are still expensive but with their increasing use, especially Lithium-ion batteries in the car industry, prices should come down like they have for other renewable energy products like solar panels and wind power turbines. For the grid on Rutland Island the thesis recommends to aim for the future and use a larger grid design with Lithium-ion batteries. The most deciding factor being that even the larger and more future oriented design had almost 30% lower price per kWh than the pre study calculations.

Acknowledgement

I have received a lot of help and support during my work on this thesis and would like to give my thanks and acknowledgements to the people who made this possible. First my supervisor at LTH, Olof Samuelsson, for giving his support to me in the writing and help with the administrative work at LTH. My advisor at RISE, Anders Lindskog, for all the support through the whole process and being so patient with me.

I would like to thank Johan Nilsson, project leader for the Andaman Islands renewable energy project that this thesis was a part of. For giving me a chance to be part of this project. I would also like to thank all the people at Teroc, especially Per-Anders Söderberg, for being so patient and helpful in answering all my questions regarding DC micro grids. Also Affectus, for providing the input data used in this thesis. Last but not least i would like to thank Hannes Hagmar, my colleague at RISE for his support and knowledge.

Contents

Chapter 1
Introduction

The background for this master thesis lies in a bilateral research agreement between the Swedish Energy Agency (SEA) and India's Ministry of New and Renewable Energy (MNRE) agreed to in 2015. The partnership is about smart grids, small isolated self sustaining grids. The vision was to perform 2-4 small-scale pilot projects to demonstrate the sustainability of local supply, distribution and use of electricity. During 2015 and 2016 three studies was therefore financed. One such study was conducted by SP Technical Research Institute of Sweden in collaboration with a number of Swedish companies. Since the start of 2017, SP is formally a part of RISE - Research Institutes of Sweden [1] and only RISE will be referred to from now on. The study was conducted on the Andaman islands, an Indian island chain located between India and Myanmar. The study was called "Feasibility study for a fossil free Andaman Islands" and had the objective to research the feasibility for a smart grid with 100 percent renewable energy supply on the islands and propose an implementation plan.

The feasibility study [2] was completed in August 2016 with the conclusion that implementation should be divided into stages. Step 1 would be to build a knowledge transfer environment, at the Technical University of Port Blair, the capital of Andaman Islands. This would then be followed by steps:

- 2a - A smart direct current grid island concept
- 2b - A smart metering system
- 2c - A biogas plant in Port Blair for utilizing waste

SEA decided to finance steps 1 and 2a during a period of 2017-2019. The aim for the project is to first build a knowledge transfer environment (as per step 1) at the local university which includes installing PV-panels on the roof and building a DC lab environment. Then (as per step 2a) to plan, model, test, and then build a small DC based micro-grid on an island south of Port Blair called Rutland Island. The companies involved in the project from 2017 onwards is RISE as project leader, Teroc for electrical grid design and Affectus for metering and measurement.

1.1 Objectives of the thesis

Step 2a is where this master thesis comes into the picture. In the pre study, Teroc, proposed a basic design for a DC based micro grid. The aim of this thesis is to build further upon this and propose a grid with components. This is important because before a grid is built on Rutland

Island, it has to be modelled, simulated and tested theoretically to save time and money. At the same time this thesis will try to answer a few fundamental questions about DC microgrids.

To do this, two scenarios giving rise to two different designs with different components will be set up. A design A, based on the current load of the Rutland community as of today, and a future design B based on the average Indian per capita electrical load. The difference between the two designs lie in cables, breakers, DC/DC converters and battery types.

To make sure each design works, three different transmission cables will be tested for each design. The two designs and the three different cable sizes (6 designs in total) will be evaluated with a set of parameters that are described below to answer which is most suitable.

The parameters we will look into further is:

- Losses - How much is the losses in individual components and how much is the total losses?
- Efficiency - How efficient is the system, on average and at the most lossy points?
- Safety and grounding - how safe is the system in question for use? What kind of breakers and fuses are needed? How big is the short circuit currents in different parts of the system?
- Cost - What is the total investment cost, payback time and cost/kWh of electricity for the different systems?

There are a number of reasons that they where chosen. The first and most simple reason is because the give a broad picture of the quality of the design. One of the goals of the project as stated in the pre study is that the grid must be replicable and robust enough to handle the conditions that exist on the island. The grid should also be able to operate for a long time and be managed locally by those living on islands without major support from the outside unless necessary. The second reason is an interview with Jan Åkesson at Telia. To learn more about which areas to focus on regarding DC grids and what kind of problems that are important. It is included in the background, but the conclusion there is that short circuit currents is one of the areas to look at, so it has been included as a parameter.

To summarize two broader questions can also be asked which this thesis will try to answer.

- A overarching question is how do you design a high quality, reliable DC microgrid with as low cost as possible?
  - Which components and factors are the most important when designing a DC microgrid?
- Which design with what components is most suitable for a grid on Rutland Island thinking both short term and long term?

1.2 Method and implementation

To answer the above questions a few steps was taken:

- 1) Do a literature study of DC grids and DC transmission

- 2) Do a dimensioning of the two grid designs with regards to PV size, batteries, DC/DC converters and fuses/breakers
- 3) Build simulation models in Matlab Simulink of the two designs
- 4) Run simulations with the above built models and analyse the parameters above

1.3 Structure of the thesis

The structure of this thesis is organised into 8 chapters. Chapter 2 and 3 describe the history and current state of DC transmission. Chapter 4 describes the thesis method with a dimensioning of the micro grid and chapter 5 describes the models used to test the designs. Chapter 6 is the results of simulations and chapter 7 is a cost analysis. Finally chapter 8 is the thesis conclusions including future work.

1.4 Limitations

This master thesis have been limited to what in the pre study is called "step 2a". To studying DC micro grids, building models and perform simulations for a micro grid on Rutland island. No physical lab work have been done with regards to this thesis.

Chapter 2

Background

In this chapter a short summary of the history of direct current up until today is given, followed by an overview of the Andaman Islands and Rutland Island, with a final look at the Indian 48V standard.

2.1 History of DC transmission

2.1.1 Early history

To understand why this thesis is based around a direct current micro grids one has to first understand the history of direct current.

The history of DC transmission could be said to be tightly bound by the early history of electric lighting. The first type of wide scale electric lighting adapted was arc lightning that produced a bright glaring light, discovered in 1808 by Sir Humphrey Davy. But this was impractical because it required high voltages (up to 3.5kV) and could only be used outside or inside very large spaces like factory's. This all changed in the late 1870s when the inventor Thomas Alva Edison perfected his incandescent light bulb.

Edison had realized that there was an untapped market for electric lighting inside domestic homes. But to make it a reality it required a whole system of electrical delivery that didn't yet exist. So thus in 1882 the Edison Illuminating Company was born, and the first 1200 light bulbs was lit by his power station at Pearl Street, Manhattan, New York in September the same year. The standard Edison choose was 110V. This was mainly because most of the loads at the time was his own incandescent light bulbs, which worked best at 100-110V [3].

The problem with Edison's DC system was that it was difficult to transport the electricity produced over long distances, without significant losses. This was because there was no way at the time to easily step up or down the voltage. This limited it to short distances and the power plant had to be placed very close to the homes it was supposed to power. It is at this time that an inventor of Serbian origin comes on the scene, Nikola Tesla. He proposed a different solution instead using alternating current and the recently invented transformer to step up the voltage for transmission, to reduce losses and then step it down again once it's reached its destination. But Edison was sceptical, and instead it was Georg Westinghouse with his Westinghouse Electric company that bought Tesla's patents and hired him as an employee. This sparked what is known as "The war of the currents", where the two companies fought over customers in an ever increasing frenzy. It culminated in 1893 when AC was used to power the Chicago World Fair. The rest is history as the saying goes and AC became the dominating standard from the start of the 20th century and for the next 100 years. This is largely because of the fact that one could easily transform the voltage up, down and therefore transport it long distances. Sources of untapped power could now be utilized. With the first example being hydro electricity from the Niagara Falls, which was used to power the city of Buffalo over a distance of 42 km in 1896 [4].

2.1.2 Development of HVDC

But DC as a means for transmission of electricity was not forgotten because high voltage AC (HVAC) had problems of it's own. With one example being the inclusion of reactive power in the AC transmission, which makes it hard or impossible to use underwater for longer distances [5]. But nonetheless for low voltage applications DC was still used and especially so inside isolated smaller systems like ships, air-planes and trains.

Slowly during the 20th century inventions of better methods for transforming the voltage of DC was about to change things. The invention of the mercury valve in 1901 and it's improvement (in 1939) by a Swedish engineer at ASEA, called Uno Lamm, made high voltage direct current (HVDC) finally feasibly. In 1954 the first HVDC commercial application was introduced with the commissioning of the underwater Gotland link (20 MW, 100 kV), between Gotland and the Swedish mainland [6].

2.1.3 Thyristors and Transistors

The mercury arc valve had among other problems the disadvantage of high maintenance requirements, being very large and having low flexibility in voltage ratings. So introduction of the thyristor (from the combination of the names *Thyr-**atron*** and *trans-**istor***) in 1956 was welcome.

In the beginning the thyristor had significant problems with losses, sometimes 50-100%. Therefore it took almost 10 years before the first thyristor based valve was used in a real commercial application in 1969 (Cabora-Bassa). The main advantages of the thyristor was that it had a drastically higher availability compared to mercury valves (98 percent compared to 83 percent) and smaller size ($1m^2$ compared to $3.5m^2$). From this point on until today we have seen an ever increasing amount of HVDC projects in the world, as of 2014 according to ABB there are over 160 projects built or planned. Especially for underwater transportation of electricity [7]. The thyristor is still used today in many projects, but in 1997 so called voltage source converters was introduced and are getting increased usage. So called because other semiconductor devices (compared to the thyristor) have the advantage that they can be both turned on and off. The thyristor only has one degree of freedom, and can therefore only be turned on, not off by control action. The most common semiconductor used for VSCs are the Insulated-gate bipolar transistor or IGBT for short [6].

2.1.4 DC and renewable energy

Today much has changed since the 1880s and the start of widespread electrification. This can be contributed to two factors primarily: 1) the invention of the transistor in 1947 and 2) the recent introduction in the last ten years of high amounts of renewable energy into the electrical grid.

A transistor only works with DC power and therefore all machines that use transistors inherently need DC power. This was not a problem for a long time because most electrical devices didn't use transistors and could run directly on AC. But slowly this has changed with the dawn of the digital era ramping up with computers in the 1980s. Now everything from your LED lightning to your cellphone, computer, TV and even home appliances are DC based. To solve this what has been used so far is a rectifier bridge, to change the current from AC to DC. But this gives a major disadvantage, namely conversion losses. This is no problem if the conversions are few. But the introduction of of large amounts of renewable energy in the last 10 years is the second factor and here a problem arises. With a large amount of renewable energy today being solar PV, which is DC based. The question arises that if producing power that is DC based and many of the electrical devices inside homes are also DC based. Why waste energy by converting it to AC and then back again?

2.2 The Andaman Islands

In this section a short introduction to the Andaman Islands will be given with some statistics and an overview of the electricity situation on the islands. Then information about Rutland island will follow which is the site of this project and the situation there.

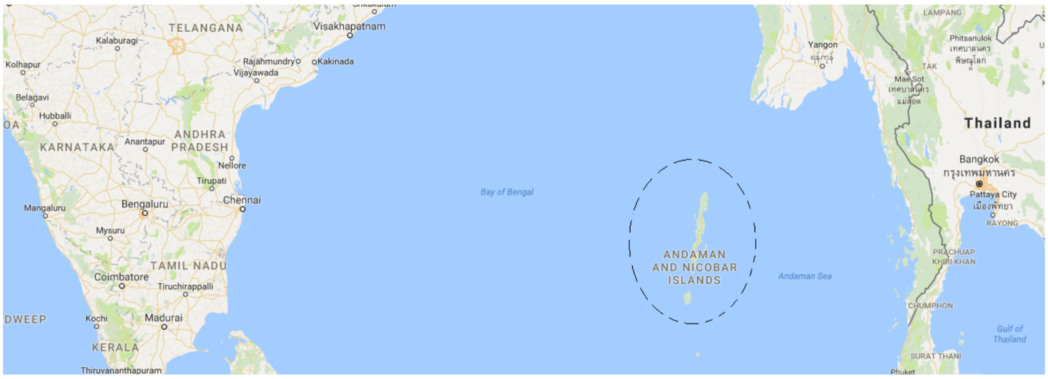


Figure 2.1: Location of the Andaman Islands in the dashed circle. Source: Google Maps, 2017

The Andaman Islands is an island chain located between India and Myanmar, approximately 1300 kilometres from the Indian coast. The island group is part of the "Andaman and Nicobar Union territory of India", an administrative territory combining the Andaman Islands with the Nicobar islands, located 270 km to the south.

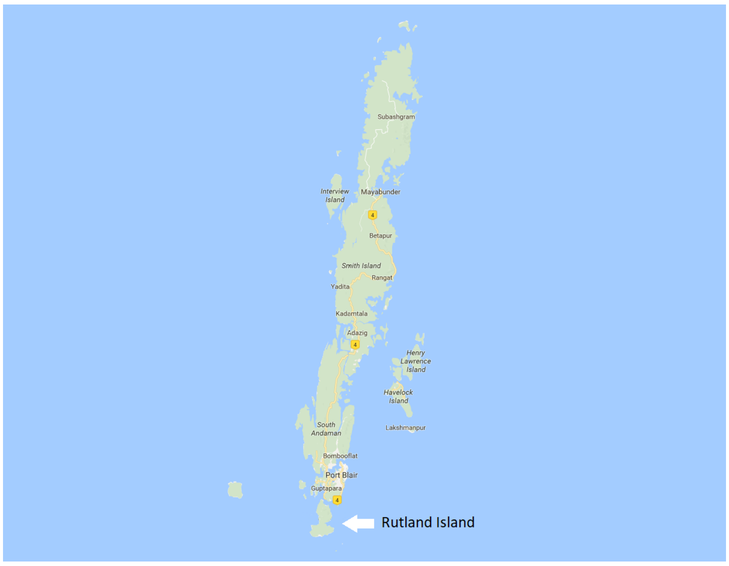


Figure 2.2: Map of the Andaman Islands with the white arrow pointing at the location of Rutland Island. Source: Google Maps 2017

The Andaman's consists of 572 different islands, of which 37 are inhabited (as of 2001 census). The three biggest islands, named the North, Middle and south Andaman Islands form a north to south chain with Port Blair the capital located on the southern island. The population is around 380000 with a majority living in the city [8].

Looking at the energy situation of the islands, with statistics from the electricity department of Andaman and Nicobar Administration. You see that as a whole the installed capacity is around 97 MW in 2015, with around 77MW of that on the southern island. Each of the islands have separate grids and power generation is spread out over 28 power houses on the north, middle and south island [9]. Deloitte in their report "*Power for all - Andaman and Nicobar*" [10], which was commissioned by the Government of India, gives the capacity at around 109 MW for the same year of 2015.

Table 2.1: Power generation on the Andaman Islands in MW. Source: Deloitte, 2015

Sector	Thermal	SHP	Solar	Total
State	62.87	5.25	0	68.22
Private	36.33	0	0	36.23
Central	0	0	5.0	5.0
Total	99.20	5.25	5.0	109.45

Looking at the above table, it says that at present, around 90% of the power is generated by private and state owned diesel generators. The rest comes from a SHP (small hydro plant), located on the middle island according to EDA&N, and a government owned 5MW solar plant outside of Port Blair. Looking at the grids, on average over the whole island chain the losses in transmission is around 30%.

2.3 Rutland Island

The project as mentioned in the introduction is going to be located on an island called Rutland Island. It is located south of Port Blair, as can be seen on the map below. It is one of the 37 inhabited islands and it takes 40-50 minutes to get there by boat from Port Blair. To get some of the information below a field trip and visit, was done as a part of the thesis, in March 2017 to the Andaman Islands and then Rutland Island.

Figure 2.3: Rutland Island, located south of Port Blair with the circled area marking the zoomed area in 2.4 is. Source: Google Maps 2017

The population in the 2001 census was around 690 people distributed among 194 homes while the 2011 census gives the population as 347 people in 119 homes [11].

Three major settlements exist, as seen on the map below, marked out in 2.4. A main location with a generator house and then two settlements outside the main location. One located 1km to the west and another one 5km to the south. The major infrastructure is located on the northern tip of the island, inside the circled area in 2.3. This includes a small generator house, police station and a small medical center, all located within walking distance. They are marked out in 2.5.

Figure 2.4: The zoomed in northern tip of Rutland Island with the numbers showing the three settlements. 1) The Western settlement, 2) Main settlement, 3) Southern settlement. Source: Google Maps, 2017

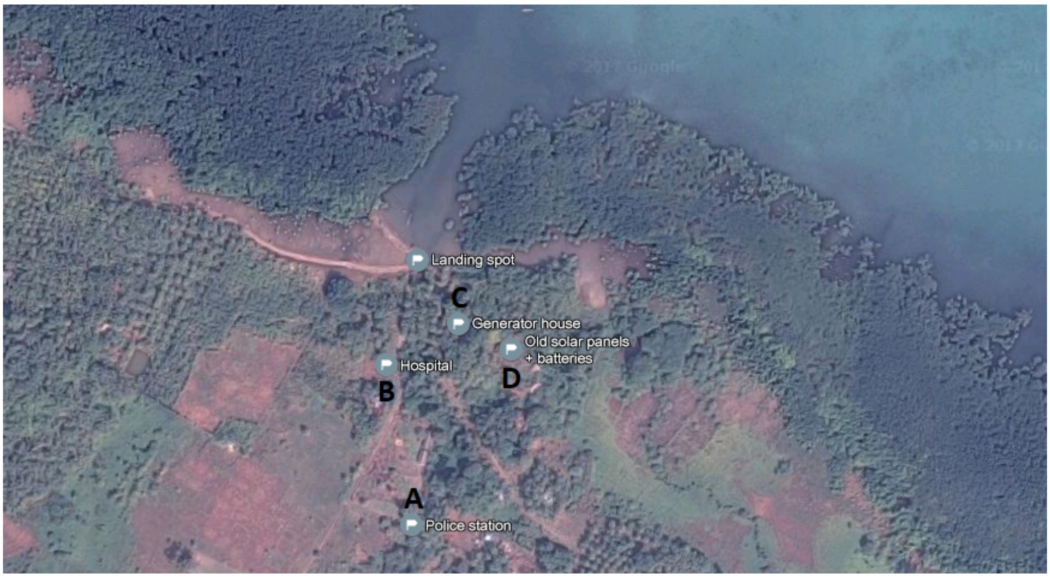


Figure 2.5: Map of the western settlement with important points shown. A) Police Station, B) Medical center, C) Generator house, D) Old solar panels. Source: Google Maps, 2017

2.3.1 Rutland power system

The current power situation on Rutland Island is based around two 12kW Diesel generators, placed inside the $100m^2$ large generator house. They are running from 5pm in the evening to 5am the next morning. This means that, currently electricity is only available 12h per day. The time is split between the two generators, so one is running for the first six hours and then the second one runs for the last six hours. The only information available is that they currently supply around 26 houses, which are split into the main settlement and the western settlement. The settlement to the west, as previously stated is located 1km from the generator house. The other settlement 5km to the south (as seen on the map above), is said to lack electricity all together.

Estimating the total population in the 26 houses is hard. But looking at total number of residents of the island, 347, divided by the number of houses, 119, would put the average number of people per house at 3. Thus 26 houses would contain around 78 people.

Figure 2.6: Diesel generators and generator house on Rutland

Distribution and transmission is currently being done by three phase 230VAC. One phase is used to supply the generator house itself with electricity and the two other phases supplying the other houses. The current diesel consumption is around 15 liters/12h. A load profile was collected during the field trip in March 2017, as seen below. It has an average daily consumption of slightly below 4 kW. It was collected with the help of Affectus which was the main project partner concerning data collection and data management.

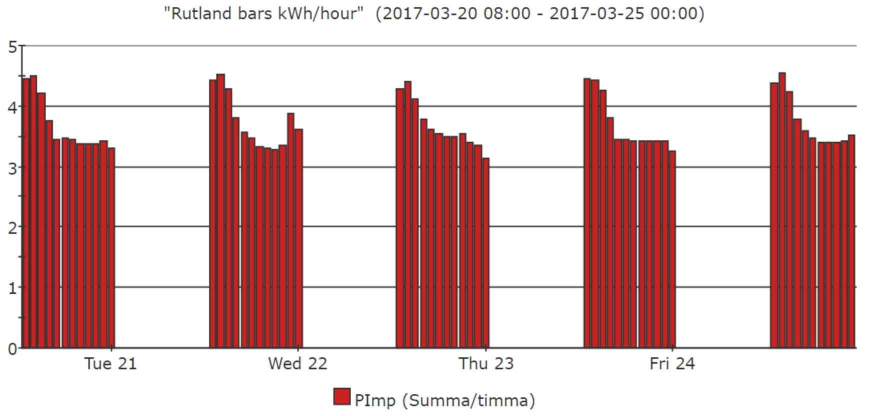


Figure 2.7: A load profile during 5 days of March 2017

Each house (according to previous visits done in 2016), has lights in the form of low energy fluorescent lamps and a ceiling fan. Some people also have other items like small TVs (but not very common). Each house has an electricity meter and a fuse. Estimating losses in the current grid is hard, but with Andaman numbers being up to 30% as previously stated, it could be assumed that Rutland Island has similar numbers or higher.

It is worth mentioning that there have been a previous attempt in the 1980's installing solar PV with battery storage to the current AC grid. This site is located close to the current generator house with a picture below showing the current situation.

Figure 2.8: Old racks for solar panels from the 1980s

The cost per kWh on Rutland Island was provided in the pre-study. For comparison, The cost of producing electricity on the main islands is around 28 Indian Rupees (INR) per kWh. With a conversion rate of 0.13 Swedish kronor (SEK) for 1 Indian Rupees, 28 INR is 3.64 SEK.

On Rutland they estimated the cost for production of electricity to be around 40-60 INR/kWh or 5.2-7.8 SEK/kWh. Which includes running the diesel generator, shipping the fuel to the island, labour cost and so on. Meanwhile the residents (on Rutland) is paying around 2 INR/kWh (0.26 SEK/kWh). This in turn means that generation of electricity is made at a significant loss per delivered kWh. Most of the cost in this case is subsidized by the Indian government. In the pre study they did a cost analysis and proposed a Cost of Energy (COE) of around 26-30 INR or 3.3-3.8 SEK per kWh for a new DC grid on Rutland.

2.4 The new Indian 48VDC standard

In the project, 48VDC was decided for distribution within homes as stated in the pre study. This was based on the fact that India have been working on a new 48VDC standard for such purposes. As of January 2017 it has yet to be completed, but it is in the draft stage. The draft [12] is included in the bibliography for full disclosure.

Summarizing the current version of the draft, the main driving force behind the initiative, just like this project, is the increasing proliferation of DC based renewable energy in India, especially solar. They argue that the improvement of technology is moving so fast that the focus should now be on energy efficiency. By using DC both in production, transmission, distribution and consumption a lot of energy could therefore be saved.

So a standard is needed for distribution that is both safe and efficient. The reason behind the actual 48V level is first and foremost that the standard is likely going to serve those in rural areas. They have little or no electricity at all meaning that grid awareness is low. They don't know the dangers that high voltage electricity poses. So the dangers should be minimized while still maintaining high enough voltage to reduce losses. The final argument is that 60V is established internationally as the upper limit for Separated Extra Low Voltage (SELV), which means anything below that is safe enough to touch directly under dry conditions.

2.5 Interview with Telia - Transient state and over voltages

Moving on to the last part in this background and the problem that arise in a DC grid. Jan Åkesson at Telia was interviewed to get more information of how they had handled this in previous projects he had been involved in.

When a DC grid is in operation and steady state, there's usually no problems. However, one should look at how power variations could trigger voltage variations in oscillatory circuits, and how this is attenuated by resistances in the system.

According to Telia there are two main issues to deal with in DC grids:

- Starting the DC network from "zero". The voltage supply of the network charges capacitances. This can cause power failure that builds energy in inductors. This can, in turn, cause over voltages.
- A short circuit causes high currents before the fuse break the current. The built up current builds up energy in the inductance of the grid and can create powerful over voltages.

2.5.1 Starting the grid

Looking at starting the grid. The grid may contain customers/loads with capacitors that has to be charged before starting. Above all, DC/DC converters are considered to contain capacitances that far exceed the capacitance of the transmission lines in the grid itself.

There are several ways to handle this:

- Start the network section by section
- Restrict power during start up (for example with series resistors)
- Shrink the effects of the energy in the inductances through diverters that burn this energy.

2.5.2 Short circuits

The second problem regards short circuits.

- The impedance of the network needs to be so low in all parts that a short circuit can blow a fuse.
- Until a fuse blows, a current is built up in the system. The current charges the inductance in the grid. This inductance will force the current to continue when the fuse blows. This in turn can cause very high induced voltages that can destroy equipment in the grid.

So to solve the above problems they give a few solutions:

- Using a freewheel diode (controversial because of safety concerns)
- Using snubbers with resistance and capacitance in series. Sometimes with a diode in series with the resistance to rectify the current through the diode.
- Shrink the effects of the energy in the inductances through diverters that burn this energy.

Chapter 3

LVDC theory

Moving on to low voltage DC theory, this chapter has the intent of presenting a general overview of how LVDC transmission works (for definitions of voltage ranges see table B.1) and the important aspects and components to take into consideration when designing a DC micro grid. This chapter is both a summary of the theory needed later on and an overview. Thus some equations will also be referred to when the grid is dimensioned in chapter 4. Each section in the review is focused on one part or component of a LVDC grid. To present this sometimes a comparison to AC is done. This is to give the reader an understanding of what the norm for grids are today, which is AC.

Distribution wise a DC grid is not very different from an AC grid. Electricity is produced by a power source ⇒ converted to a higher voltage for transmission ⇒ transmitted ⇒ converted to a lower voltage ⇒ distributed to customer ⇒ the electricity is consumed.

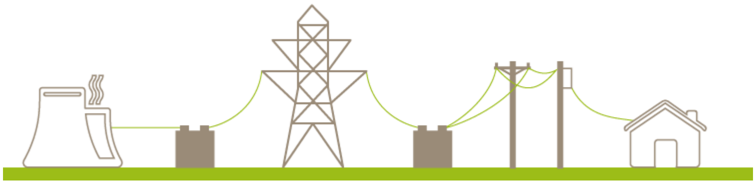


Figure 3.1: The simplified energy supply chain. Source: Australian Market Operator [13]

It is the way that a DC grid is configured which is different, as we will see here.

3.1 DC Micro grids

Starting with the definition of a micro grid. It is somewhat diffuse and different definitions exist, but the US department of energy [14] defines it as:

"A micro-grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro-grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."

A micro grid can be both AC and DC based with AC being the current norm. DC based micro grids is a very new concept still in the research phase. Talking about a grid being AC or DC based in this case refers to the way the electricity is transmitted and distributed, not if the electricity produced or consumed is AC or DC based. Below an example of a micro grid can be seen.

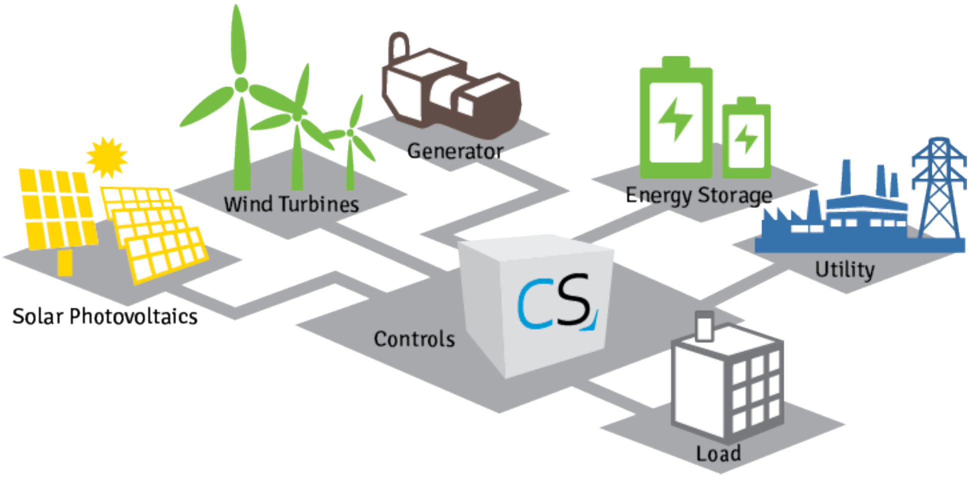


Figure 3.2: A simplified overview of a micro grid. Source: Sustain Innovate [15]

3.2 Grid architecture and bus topology

Moving on to grid architecture. The literature gives the two most common ways to organize a DC grid as monopolar and bipolar [5].

Monopolar uses one energized conductor and one zero energized conductor for ground (which can be seen in the figure below). This type of configuration is also a one phase configuration opposed to bipolar which is two phased. It is good from a economical perspective but depending on country, monopolar is sometimes forbidden. This because the ground current can cause erosion to nearby pipes and/or metal objects. But it is currently allowed in Europe and often used in for example underwater cables.

Bipolar is what this grid will use. As the name suggests it uses two conductors, one for plus and one for minus, with a zero energized ground in the middle. Bipolar is naturally more expensive because it uses double the cable material. But it has the advantage of flexibility, for example if a fault is detected in one of the conductors, it can be used as monopolar for a short time and transmit half the power. If the two conductors have separate grounds, the phases can be operated separately if deemed necessary (as two fully powered monopolar systems) [16] [17].

3.3 Voltage levels

Voltage level for DC grids is a debated subject. In this project, as will be mention in Chapter 4, the voltage levels talked about for transmission is between 350-380V for one phase or 700V-

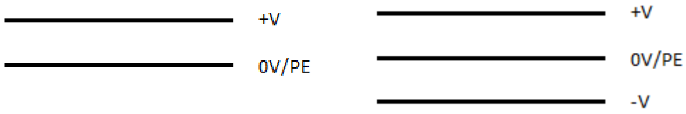


Figure 3.3: Monopolar and bipolar bus topology

760V for two phases. For distribution within homes the Indian standard of 48V will be used [2]. But depending on literature and how far back you go the opinions differs significantly on which voltage to use. At the moment no universal standard for DC grids have been established. In USA the emergence alliance is setting the standard for data centers and aiming for 380Vdc/24Vdc [18]. As debated in the Indian standard for 48V distribution, there are many aspects to take into consideration, primarily losses and safety.

3.4 Cables

Cables is the backbone of a DC micro grid. They are the medium in which the current is transmitted from point A to point B. Just as in an AC grid, the cables in a DC grid need to be properly dimensioned in regards to factors like losses and maximum current carrying capacity. In a DC system, cables can be modelled differently depending on if the grid is in steady state or transient state and what aspects of the system you are interested in looking at. This is because in steady state the frequency is naturally zero, all inductances can therefore be considered short circuits and all capacitors open circuit [19].

Because the small size of the system looked at in this thesis and the longer time periods we will only take into account the resistance in the cables. But for a more detailed modelling and larger more complex systems (especially when looking at sudden changes in the system on short time scales) you have to look at at all the four factors below:

- Series resistance
- Series inductance
- Shunt capacitance
- Shunt conductance

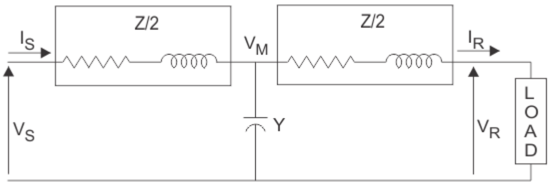


Figure 3.4: Model of a transmission cable. Source: Electrical4u

Chapter 13 of the book "*Electric Power Generation transmission and distribution*" [20] gives the equation for calculating the resistance in a cable.

The resistance can be calculated by:

$$R = \frac{(\rho * L)}{A} \tag{3.1}$$

ρ is the resistivity of the conductor material in Ohm/m, L the length of the cable in meters and A the cross section in square millimetres.

The cross section depends on country standards and varies. USA and Canada use the American Wire Gauge system. Europe, India and most of the world use the internationally recognized IEC60228 standard, which is measured in square millimetres (as in the above equation). If nothing else is mentioned it is assumed that all references to cross section dimensions in this essay are in the IEC60228 standard.

Resistance in a transmission line is also dependent on temperature and rises linearly with:

$$R2 = R1(\frac{T + t_2}{T + t_1}) \tag{3.2}$$

with R2 being the second temperature at time t2, R1 resistance at initial temperature t1 and T the temperature coefficient of the conducting material. When modelling, this parameter will not be taken into account.

One of the two factors mentioned when dimensioning cables is the ampacity or current carrying factor. It defines the maximum amount of current that can flow through a cable during longer periods of time without causing degradation or damage to the cable. In appendix B and figures B.1 and B.2 there is an overview of of the current carrying capacity for different cross sections. This will be referred to later in the essay when the two grid designs are dimensioned.

Moving on to the losses in the cable. In this essay it is assumed that they are only dependent on the total resistance of the cable and not the impedance which briefly arise in transient state.

The voltage drop in the cable is given by:

$$U_{drop} = R_{cable} * I \tag{3.3}$$

And the power loss by:

$$P_{cable} = U_{drop} * I \tag{3.4}$$

If combining the two we get the relationship between power losses in the cable and resistance:

$$P_{loss} = R_{cable} * I^2 \tag{3.5}$$

In an actual circuit or system you have to take into account both the positive conductor and the negative/neutral conductor when calculating losses. So if the distance from production to consumer is for example 1000 meters, the length of cable when calculating the value of R_{cable} is 2000 meters.

3.5 Safety, faults and protection devices

Moving on to the situation of safety, faults and protection devices. In this section all three will be briefly discussed. What the dangers in a DC grid are, what kind of grid faults are most likely to occur and how to protect the grid and people from harm. For much of the information on faults, breakers and short circuit currents, two documents from ABB [21] and Schneider Electric [22] have been used. They will both be frequently referenced to.

3.5.1 Safety

As defined in IEC 60038 B.1 the big risk for low voltage DC transmission is electrical shock. This is especially true for the 700V level. For the 48V level, the reason as talked about in the Indian 48V standard that is was chosen was because it is deemed high enough to reduce losses but low enough (<60V) to not harm a person.

3.5.2 Faults

In the document from ABB they give an overview of fault scenarios in: networks isolated from earth, monopolar networks and bipolar networks. This project as stated earlier is bipolar based, so only that is summarized below. But the ABB reference gives a good overview of all three for the interested. Three fault scenarios drawn up are:

- **Fault A - pole to pole fault**
  A fault between the positive and the negative pole. The fault current is dependent on the full source voltage U.

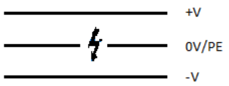


Figure 3.5: Pole to pole fault

- **Fault B or C - positive or negative pole to earth**
  A fault between either of the polarities to earth. The fault current now depends on U/2.

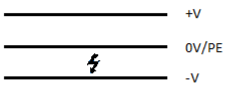


Figure 3.6: Pole to ground fault

They conclude that a phase to phase fault is the most likely to occur.

3.5.3 Breakers and fuses

To prevent harm to the grid or to people in the case of a fault, protection devices need to be in place and break the current as quickly as possibly. They broadly involve fuses and circuit breakers (CB).

Circuit breakers are split into low voltage power CBs, molded-case circuit breakers (MCCB) and isolated-case CBs [23]. A circuit breaker is used to break the current and force it to zero. Breaking the current in a DC circuit gives a different problem in this regard then AC. With AC there is a natural passing through zero or zero crossing (as referenced in the picture below) which breaks the current. But DC does not pass through zero, so in the event of a fault the current has to be forced to zero giving rise to lightning arcs.

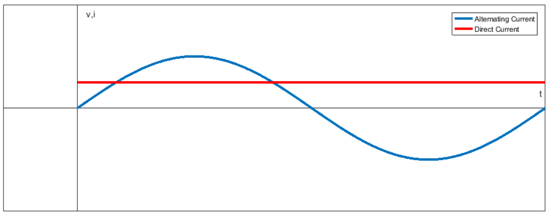


Figure 3.7: AC vs DC

The formula describing what happens when the circuit breaker is lifted to reduce the current is:

$$U = L * \frac{di}{dt} + Ri + Ua \tag{3.6}$$

Where L is the inductance of the circuit, U the voltage of the supply source, R the resistance of the circuit and Ua the arc voltage.

For the arc arising to extinct, di/dt < 0. This also means that:

$$L * \frac{di}{dt} = U - Ri - Ua \tag{3.7}$$

So when the arc voltage becomes high enough the current will go to zero. This in turn means that to get a gradual safe reduction of the fault current, the arc has to be extended and cooled, the arc voltage thus being increased until di/dt is less then 0. For categorizing the breakers themselves a few common parameters are used:

- Operation voltage *Ue* - Determines the application of the breaker
- Uninterrupted current *Iu* - The current that the breaker can carry for a indefinite time, size of the breaker
- Current *In* - The value of the current defining the trip limit
- Ultimate short circuit breaking capacity *Icu* - The maximum short circuit current that the breaker can break twice in a row
- Rated service short-circuit breaking capacity *Ics* - Maximum short circuit current the breaker can break three times in a row
- Rated short-time withstand current *Icw* - The current that the breaker can carry in closed position during a short time

- The short-circuit current at the installation point of the circuit-breaker *Ik*

When determining the circuit breaker to use in a system the steps are to:

⇒ 1) determine which network topology you have
⇒ 2) determine the operational voltage of the system *Ue*
⇒ 3) determine the short circuit current *Ik* at the breaking point, $Ik \lesssim Icu$
⇒ 4) determine the current Ib absorbed by the load, $Ib \gtrsim In$

3.5.4 Short circuit currents

For calculating the short circuit current (Isc) in a DC auxiliary system, the standard IEC 61660-1 can be used. It gives the components contributing to the short circuit current as:

- Smoothing capacitors
- Stationary batteries (For example Lead-acid or Lithium-ion)
- Rectifiers
- D.C. motors, with independent excitation

Where the first two is potentially interesting in this project. But only the contribution of batteries will be taken into account, because of reasons discussed further in the chapter on simulations of short circuit currents.

The first basic thing to understand is that a DC grid no matter the size, behaves the same way as a small circuit would when it comes to short circuits. This means that the two factors contributing to the size and behaviour of the Isc, is the total resistance and the total inductance in the circuit. The resistance being important when calculating the size of the Isc and the inductance affecting the L/R constant of the circuit. The L/R constant is in turn used to determine the rise time of the short circuit current. Below is the IEC method for calculating the contribution of a battery to the short circuit current in a DC auxiliary system.

The peak short-circuit current is:

$$ipb = \frac{Eb}{R} \tag{3.8}$$

The steady-state short-circuit current is estimated as:

$$ikb = \frac{0.95 * Eb}{R + 0.1 * Rb} \tag{3.9}$$

R is the total resistance in the circuit with R = 0.9*Rb + Rbl + Ry.

Rb is the resistance of the battery in case of a short-circuit. This value is specified by the manufacturer of the battery. **Rbl** is the resistance of the conductor in the battery branch. **Ry** is the resistance of the common branch with other supply sources (if it exists). **Eb** is the open-circuit voltage of the battery (the voltage at 100% state of charge).

For more information on the calculation of the L/R constant of a DC circuit and how to calculate the rise time, see the document referenced earlier from Schneider Electric.

3.6 Power Electronics

Moving on to power electronics. From the historical perspective it is clear that what made DC possible in scale was the invention of power electronics in the 1960s. Depending on what source you read, definitions vary for what counts as power electronics. Some sources count mercury valves as power electronics and others only count the introduction of the thyristors and onwards as power electronics.

3.6.1 Converters

The type of power electronics used depends on what your purpose for conversion is. They are split into three groups.

AC to DC conversion - Rectification

The conversion of AC to DC is called rectification. If only diodes are used, the process is uncontrolled, and power flows uninterrupted. As mentioned in the historical overview both thyristors and Voltage source converters (with IGBTs) are used for this process to control the flow. An article [24] from IEEE Energytech gives a good overview. With Rectifiers usually grouped into single-phase and three-phase converters. Single-phase for extra low or low voltage DC applications and three-phase converters used in HVDC projects.

VSCs can then grouped in to: two level converters, three level converters and Modular Multi-Level Converters. Which one to use of course depends on what your intentions are and cost considerations [25].

The process of rectification is what occurs in all power adapters, cell phone chargers which is plugged into the AC wall outlet.

DC to DC conversion - Stepping up/down the voltage or regulating the power flow

The most common type of conversion is the DC/DC conversion which is used inside most modern DC based machines. For a project of the size which this thesis revolves around, this is the most important.

They can be split into:

- Linear converters, uses a variable resistor or transistor to get a voltage divide with the load. Inefficient because of the losses over the resistor/transistor
- Switched converters, uses transistors as switches to regulate the current flow and voltage level.

DC to AC conversion - Inverter

The conversion of DC to AC is called inversion. A process very common and always used whenever a DC source like solar PV is used and has to be converted to AC for a standard grid.

3.6.2 Losses in Power electronics

One important aspect of power electronic converters is the losses that arise in the conversion process. Both the consumer and manufacturers naturally want to reduce these losses as much as possible.

Vargas [26] in his essay "*Why Low Voltage Direct Current Grids?"* gives a good overview of the power electronic losses. He splits the different types of losses into: conduction losses, losses in power switches, diode forward & recovery losses, transformer losses and control integrated circuit (IC) losses.

Conduction losses includes ohmic losses in switches, capacitors, inductors and the like. It follow the same equation as cable losses, $P_{loss} = R * I^2$, where R is the resistance of the component that the current I of the circuit is flowing through.

Losses in power switches is the losses that occur in the time between the on and off state of a switch. It is expressed with:

$$P_s = \frac{1}{2} * V_d * I_d * f_s * (t_{c(on)} + t_{c(off)}) \tag{3.10}$$

Where V_d is the voltage across the switch, I_d the current through the switch, f_s the switching frequency and $t_c(on)$ and $t_c(off)$ the on and off times.

Diode forward/recovery losses is the losses because of the non zero voltage drop across the diode in on state and the recovery losses when the diode is off.

The on losses can be approximated by:

$$P_{D(on)} = V_{D(on)} * I_{D(average)} + r_{T(on)} * I_D^2 \tag{3.11}$$

Where V_D is the voltage across the diode, I_D the current through the diode and $r_{T(on)}$ the equivalent resistance.
And the off losses by:

$$P_{D(off)} = \frac{1}{2} * I_{RRM} * Vo * t_{rr} * f_s \tag{3.12}$$

Where V_0 is the output voltage from the diode and t_{rr} the time that the diode is in recovery.

Thus giving the total loss in this case as $P_{Diode} = P_{D(on)} + P_{D(off)}$

Transformer losses is the ohmic losses in windings and cores of the transformer.

Control integrated circuit (IC) losses is the power lost because the ICs in the converter requires power to run. Given by the equation:

$$P_{IC} = V_{IC} * I_{IC} \tag{3.13}$$

3.7 Energy storage

One of the important parts of a micro grid is energy storage. Without connection to the grid some kind of storage is needed for absorption of excess energy in the grid, load levelling and emergency power. The most common type of energy storage used is flywheels and batteries, where the latter is used in this project.

The two most common types of batteries are Lead-acid and Lithium-ion. Lead-acid has a long history of more then 100 years while Lithium-ion was invented in the 1970s and didn't get it's breakthrough until the 1990s [27].

The most common parameters for batteries are (using a summary from MIT [28]):

- State of Charge (SOC) - The % of energy in the battery compared to the maximum level
- Nominal Voltage - The voltage at normal state of charge
- Nominal capacity (Ah) - The capacity at nominal voltage
- Charged voltage - The voltage at 100% SOC
- Cut off voltage - The minimum voltage level before the battery stops working
- Cycle life - How many times a battery can be discharged/charged
- Internal resistance - Resistance between the two poles with no load
- Energy Density (Wh/L) - Amount of energy in the battery per volume

S. Podder and M. Z. R. Khan in their paper [27] "Comparison of Lead acid and Li-ion Battery in Solar Home System of Bangladesh" gives a good overview of the difference between Lead-acid and Lithium-ion batteries.

Their conclusion is that Li-Ion has 1/6 of the charging time of Lead-acid but still has 2-3 times better cycle life. The negative aspects is that Li-Ion batteries are more unstable (especially if overcharged) and the recycling of them is more costly then Lead-acid. When comparing at the economic level, Li-Ion is better even though it has a higher cost per kWh, mainly because of its superior energy density.

For modelling of batteries different ways exist but a first order version can be seen below.

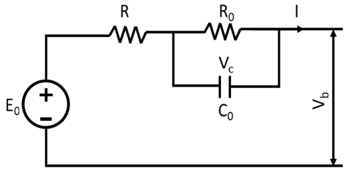


Figure 3.8: First order model of a battery. E0 is the battery voltage, R0 the ohmic resistance, R the polarized resistance and and C0 the battery capacitance. Source: ResearchGate

3.8 Energy generation

The last important aspect to talk briefly about is the source of energy in a micro grid. As seen in figure 3.2 this can be many possible sources from solar PV, to wind power and generators. In this grid as mentioned later, only solar PV is included, so a brief introduction to that is given here.

Solar PV works by sunlight hitting the individual silicon cells in the modules, thus generating a current. Usually a solar module is made up of cells, and then a Photovoltaic array is made up of a number of modules. A simple first order model of a solar cell can be seen below.

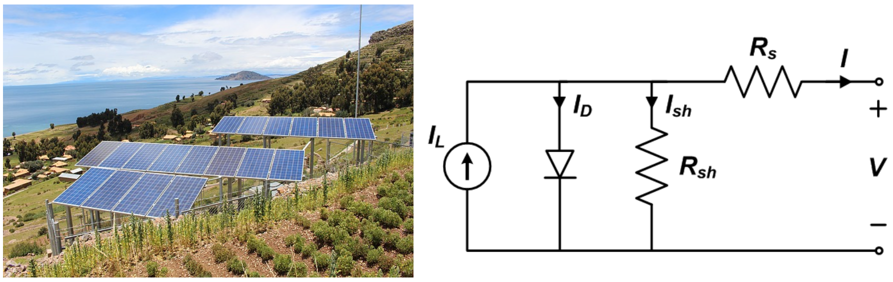


Figure 3.9: To the left three PV arrays. To the right a first order model of a solar cell. Source: pvpmc.sandia.gov

Chapter 4

Micro grid design

The micro grid layout, components used and the dimensioning of the two different designs being compared in the thesis is described here. As mentioned in the introduction design A is based on a current load profile and B a future load profile. The difference in the two lies in cables, power electronic converters, breakers and battery types. They have the same type of renewable energy generation and basic grid layout. A short introduction is also given to the tools and thinking used when dimensioning the micro grid.

4.1 Design method and tools used

The method and thinking used when designing and dimensioning the micro grid has been a combination of theory and trial & error. The basic thinking has been to first look at the layout of the site at Rutland Island. Then continuing by looking at the current load pattern, how the community at Rutland Island consume electricity today. The dimensioning itself started with using the tool described below, Homer Microgrid Analysis Tool. To get an approximation of the size of solar PV, battery energy storage and load size. Then last but not least dimensioning the other components like cables, power electronic converters and breakers.

4.1.1 Homer Microgrid Analysis Tool

One of the tools used as mentioned above while dimensioning the grid, is the Homer Microgrid Analysis Tool. A student trial license was used which gives unlimited access for 30 days.

The software has the main purpose of setting up simple schematics of micro grids with energy storage, power sources and loads. Then running simulations to check all possible combinations of the above to match the load with their respective costs in mind.

4.2 Basic micro grid layout

First off when designing a micro grid is looking at the layout of the site. It is seen below from generation to consumption in the houses around and close to the generator house at Rutland. Because of the lack of information on which houses the current diesel generators supply a few simplifications have been made. It assumes that in this phase of the project only the western most settlement is included and supplied by the DC grid. The western settlement is as previously stated, around 1km from the generator site. So the police station, medical center and any potential houses next to the generator house is not included in this phase of the project.

Figure 4.1: Layout of the micro grid

In the layout above two assumptions have been made, the first is that the main hub or focal point for distribution of electricity is the old generator house. This is where the batteries will be stored. In all scenarios we have assumed that the energy generation is in the form of solar PV panels. They are placed at the old PV site mentioned in the Rutland background information,

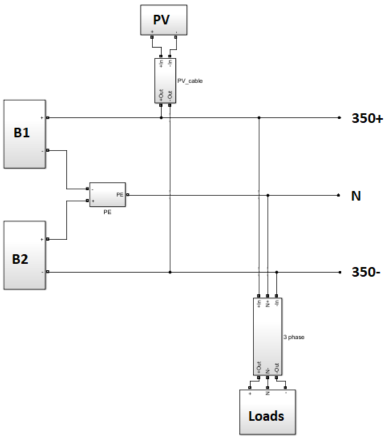


Figure 4.2: System overview with B1 and B2 being the batteries, PV the solar PV and Loads all the houses

which is around 100m from the generator house. The reason for batteries and solar PV not just being placed at the western settlement, is that in the future more houses can be included next to the generator house or further 5km to the south.

4.3 Load

No information on exact distances between the 26 houses being supplied by this grid is available. So a rough estimate has been assumed to an equal distance of 50m between each group of houses. The 26 houses have been equally split into 13 houses per 350V phase. In the figure below the approximate layout of the houses can be seen (as modelled in Simulink).

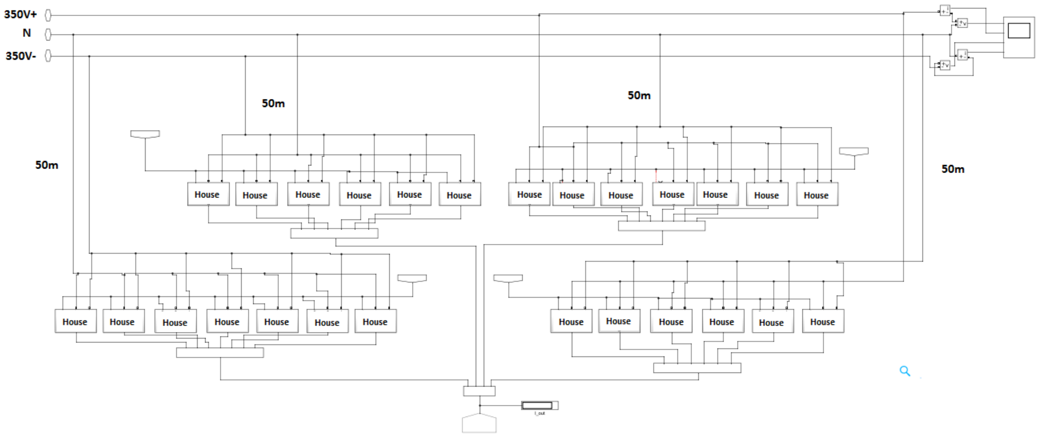


Figure 4.3: Layout of the houses in the western settlement

4.3.1 Load behaviour

The load behaviour for the houses above has to be based on a realistic consumption profile. So the residential profile from the Homer software has been used. The loads in Homer is based on a range of profiles provided by the software, from residential to industrial consumption. The profile chosen is then scaled up depending on what yearly average load you input into the software. The residential profile has used as a base profile for load input here. The profile is scaled by a factor given by homer for design A and B. The base curve as seen in Homer can be seen below. It follows what you would expect from residential consumption. A peak in the morning and lunch times when food is prepared, followed by a dip and then a peak during evening activities.

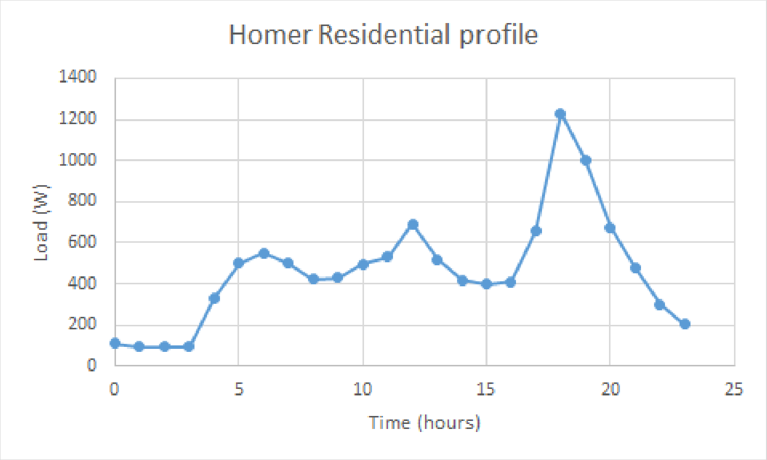


Figure 4.4: The Homer Microgrid residential profile over 24h

4.4 Distribution

4.4.1 Electrical system

Below is an image of the basic micro grid layout envisioned by Teroc that both the designs in this thesis are based upon.

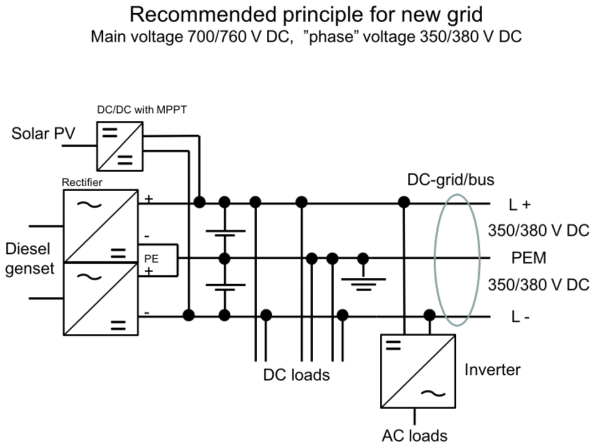


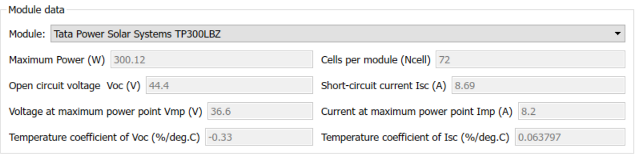
Figure 4.5: The basic micro grid design envisioned by Teroc in the pre study

In the pre study the grid voltage are suggested as floating between 700V-760V (350-380V per phase) for transmission and a set 48V for distribution. The bus topology has been set to a bipolar system consisting of two phases and a neutral with protective earth in the middle. A note is that in the above image diesel generator sets can be seen. This is not included as part of this thesis but proposed in the pre study.

4.4.2 Power generation

Solar PV will provide electricity to the grid with the original suggestion in the pre study being 10 panels of 300Wp on 10 strings, equalling 30kWp in total. This was to match the 24kW that is currently installed in total diesel capacity.

This is scaled up slightly for design A and a lot for design B. The idea was also to use Indian made solar panels. So in this case the TATA Power Solar TP300 series panels will be used, because TATA is one of the biggest manufacturers of solar panels in India. The series has modules ranging from 280W to 310W panels. They have an efficiency ranging from 14.10 to 15.25%. An example with information from the 300W version is seen below.



Module data
Module: Tata Power Solar Systems TP300LBZ
Maximum Power (W) 300.12
Cells per module (Ncell) 72
Open circuit voltage Voc (V) 44.4
Short-circuit current Isc (A) 8.69
Voltage at maximum power point Vmp (V) 36.6
Current at maximum power point Imp (A) 8.2
Temperature coefficient of Voc (%/deg.C) -0.33
Temperature coefficient of Isc (%/deg.C) 0.063797

Figure 4.6: The TATA Power TP300 PV panel parameters

In the pre study also wind power and hydro power was suggested in combination with solar PV. Both were in the end considered not feasibly. Wind power because no spot with favourable wind conditions could be found and the hydro alternative because it was already used to provide drinking water.

Input data for the solar panels are Global Horizontal Irradiance (GHI) in W/m^2, collected by a weather station near Port Blair (at 11.65 °N, 92.75 °E) during 24 hours on the 29 April 2007. The graph of the data can be seen below.

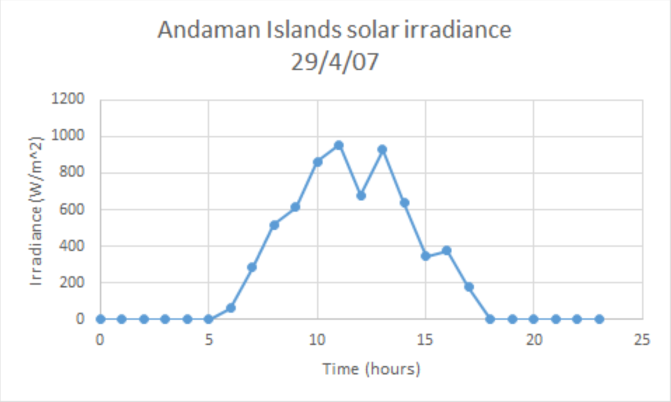


Figure 4.7: Andaman solar irradiance over 24h, source: NREL

4.4.3 Cables

Cables are an important part of a grid as previously mentioned in the LVDC theory section. In the pre study no exact cross-section or cable type was mentioned for neither transmission or distribution.

So three different types of cables are used:

- PV cable - from the PV array to generator house
- Transmission cable - from generator house to western settlement
- Distribution cable - for distribution to the houses

Normally when dimensioning an AC grid, you would look at a standard telling you what a maximum percentage of losses you should aim for and which cables to pick. But because no unilateral standards exist for DC grids some assumptions have to be made. For the PV and distribution cables a maximum loss of 5% will be aimed for in dimensioning. For the larger transmission cable, a trial and error method will be used and three different cable cross-sections for each designs will be tested and evaluated. We will use the Swedish standard for making sure that all cables chosen can handle the maximum nominal current flowing through them. We will also assume that all cables are buried because that gives bigger flexibility in cable sizes and natural resistance against the elements.

The cable used for PV transmission will be a 100m single phase cable. It was chosen because it was deemed to be the most common type of cable used for PV transmission. Cross-section depends on the amount of installed PV so that will be suggested during designing below.

After discussions with Teroc, normal EKKJ 3-phase cable used for AC transmission will be tested for the transmission part between the generator house and western settlement. Two phases acting as positive and negative, and the third acting as neutral. Looking at for example Swedish standards (included in appendix B) for cables, cross-sections up to $16mm^2$ are always copper cable and above $25mm^2$ they are made of both copper and aluminium depending on country.

The distribution cables from transmission line to each group of houses, with a length of 50m, depends on the size of the load. But it will be a single phase cable, cross-section again suggested below.

4.4.4 Power electronics

To convert the output voltage from the solar panels, to the grid voltage and maximize output power, a DC/DC converter with an MPPT from the company FerroAmp was chosen, their Solar String Optimizer. It has a maximum output of 6kW and a maximum input current of 9A. To match our total output current from the solar panels, which will be higher the what one SSO can handle, a number of them will be put in parallel to match the output.

For stepping down the transmission voltage to the 48V distribution level, DC/DC converters will be used, talked more about below.

4.4.5 Energy storage

Batteries will be used for energy storage. Both Lead-acid and Lithium-ion was mentioned in the pre study as potential candidates so both will be tested, in one design each. One battery bank will be installed in each phase, working as load balance, energy storage and setting the grid voltage. The aim is for the nominal voltage in all cases to be around 350V per battery bank. But depending on stack configuration it could be both a bit higher or lower. Also as mentioned in the theory, the actual battery voltage when fully charged is different for both Lead-acid and Lithium-ion. For Lead-acid it is around 9-10% higher, which for a nominal voltage of 350V would be about 380V when fully charged.

4.5 Dimensioning of design A

Design A is focused on replacing the current energy situation with a better and more robust, renewable DC grid but assuming that the load is about the same as today.

4.5.1 Scenario

The scenario that this design is based around comes from the load data collected at Rutland in March 2017 and the current energy situation there. As previously stated power is available for 12h between 5pm and 5am, averaging around 4 kW. Both 15 minute values and hourly values were collected, but only hourly values are used in this thesis.

Using the above number of 4kW the consumption has then been spread throughout the day over 24 hours, but with the same average load of 4kW. This gives an average daily consumption of $4kW * 24h = 96kWh/day$. This daily consumption has been input into the Homer simulation software in combination with its residential profile. The calculations gave a maximum possible peak load during the year of 17.82 kW and a scaling factor of 8.52 to be applied to the residential profile. The resulting load profile can be seen below with an average consumption throughout the day of 4kW.

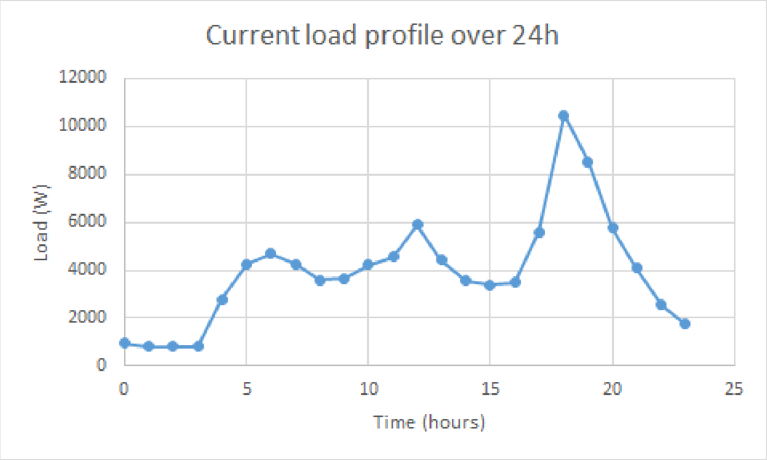


Figure 4.8: The current load profile over 24h

4.5.2 PV

Starting with the solar PV, 30kWp was suggested in the pre study. This was done before the measurements at Rutland in March 2017, so a new homer simulation gave 37kWp installed PV. Using the suggested panels with the 285W version and 10 strings of 13 panels each, would give 37.05kWp. With 10 strings we will also use 10 FerroAmp SSO, one on each string.

4.5.3 Battery design

Moving on with the battery type, this design will use Lead Acid batteries. Each battery bank will be made up of 12V batteries. In stacks of 28 it would give a nominal voltage of 338V and around 366V as fully charged. The simulations in Homer gave a recommended total battery size of 280kWh at 672V or 140kWh per 336V battery bank, assuming equal load between phases. This translates into a total Ah capacity of one battery bank at around 414Ah. Depending on connection, for example putting them in parallel blocks of four would give 103.5Ah per 12V battery. To get this we thus need $2 * 28 * 4 = 224$ batteries.

As an example battery to be used, the 12V/109Ah (12PVB121) Enersys Powersafe has been used. It has an internal resistance of 6.62mΩ. This translates into $28 * 6.62m\Omega = 0.185\Omega$ per 336V battery pack. Using four of them in parallel would thus give a total internal resistance of $\frac{0.185}{4} = 0.0462\Omega$.

4.5.4 DC/DC Converters

Looking at DC/DC converters for stepping down the voltage from the phase voltage of 336V, to distribution voltage of 48V. The factors considered are primarily maximum output power and the output current. Assuming 26 houses and a peak load of 17.82kW gives each house a maximum power consumption of 685W. At 48V the load side current would thus be 14.27A per house. To comply with this the converter chosen was the *Power supply SNT13048* from FEAS, which has a top efficiency of 91% according to the data sheet. It can handle an output current of 15A and has a DC input voltage of 120-400V, which also complies with the maximum phase voltage of 366V when fully charged. The maximum possible load per house would be 720W.

4.5.5 Cables

For cable dimensioning equations 3.1 and 3.4 are used. As stated in the theory primarily factors to look at is losses in the cable and the current carrying capacity. Starting out with the PV cable, assuming a maximum possible production of 37kWp and a nominal phase voltage of 672V would give the maximum possible current in the cable as 55A. At minimum this would require a cross-section of $10mm^2$, looking at table B.1. At 100m and trying to aim for a maximum transmission loss of 5% as previously said, if using $10mm^2$ that would give a maximum loss of 2.78%. For transmission assuming a maximum load of 17.82kW at 672V would give the maximum current as 26.3A. Here three different cable cross sections was tested which all pass the limit. Those are $6mm^2$ (43A), $10mm^2$ (60A) and $16mm^2$ (80A). With $6mm^2$ being the default value if nothing else is mentioned. The reason they were chosen is because when talking to Teroc, $6mm^2$ was mentioned as a possibility and at the same time having in mind trying to keep the weight of cables down.

For distribution a 50m cable will be used and if each of the four house groups has a maximum load of $17.82/4 = 4.45kW$ that would give a maximum current of 13.25A. Again aiming for maximum loss of 5%, the minimum possible cable would be $1.5mm^2$ according to table B.1. But trying to have a margin of error, a $4mm^2$ being the next step would give 1.67% maximum losses.

4.5.6 Grid protection

Moving on to the last part which is protection in the system. To do a proper dimensioning of this, short circuit currents is needed. They will simulated with results presented in chapter 6.4 and breakers suggested 6.4.3.

4.5.7 Summary

In summary what will be tested in this design is:

- 37kWp TATA Solar 285W Panel
- $10mm^2$ PV cable
- $6mm^2/10mm^2/16mm^2$ 3-phase cable for transmission
- $4mm^2$ distribution cable
- 12V Energysys Lead-acid batteries
- 720W 15A FEAS DC/DC converter

4.6 Dimensioning of design B

In this design we have chosen to look at a future scenario, possible 2020 or further on where the load is heavier and thus have bigger breakers, more robust DC/DC converters and thicker cables. Lithium-ion batteries are used because of the current trend towards them in the car industry and in other micro grid projects.

4.6.1 Scenario

The scenario that this design is based around comes from the average electricity use of 765kWh/year/capita in India 2013 (data [29] from the World Bank). The data was combined with the Residential profile in Homer and linear scaling was again used to get the load for a whole community, with Homer giving a scaling factor of 18.5. For a population of hundred inhabitants, an average load would be 8.7 kW (corresponding to 209 kWh/day) and a peak load of 38.9 kW.

The above assumes slightly higher population in the 26 houses. Current estimates as stated in the background would be 26 houses and 3 in every house. But you can assume that a future scenario with higher load also has more people in total.

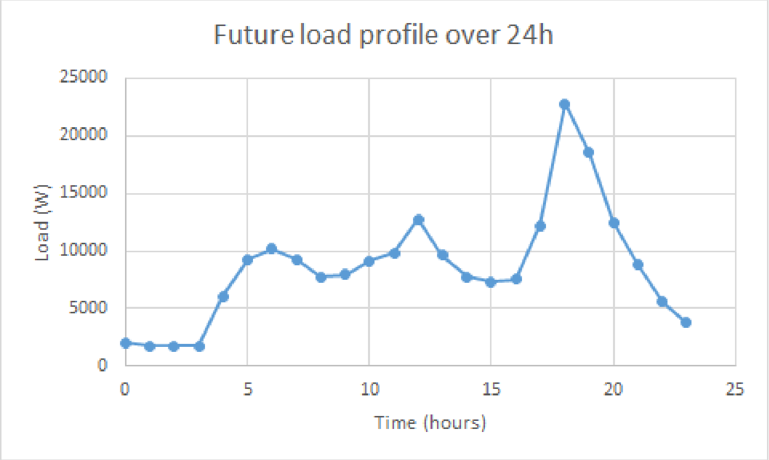


Figure 4.9: The future load profile over 24h

4.6.2 PV

Again quickly first mentioning the solar PV. In this design the homer simulation software was run to optimize for cost between battery storage and solar PV. The conclusion was that 86kWp of solar PV was a good choice to match the load. With the TATA Solar 285W panel and 20 modules on 15 strings gives 85.5kWp. This gives 15 FerroAmp SSO, one on each string.

4.6.3 Battery design

Moving on with the storage batteries, this design will use Lithium-ion batteries. Each battery bank will be made up of 12V batteries in stacks. The battery type used is LiFePO4 which has a nominal voltage of 12.8V. So to get a phase voltage of around 350V, they will be stacked as 28, which give us a nominal voltage of 358V and around 425V charge voltage. The simulations in Homer gave a recommended total battery size of 336kWh at 720V or 168kWh per battery bank. This translates into around 500Ah in total for one battery bank, or 125Ah per 12.8V battery if putting four in parallel. As an example battery to be used, the 12.8V/150Ah (SB150) from Smart-Battery has been used. If using four stacks you get 600Ah in total and $2 * 4 * 28 = 224$ batteries. The battery has an internal resistance of 10mΩ. The total internal resistance for one battery bank is thus $\frac{0.28\Omega}{4} = 0.07\Omega$.

4.6.4 DC/DC converters

Looking at DC/DC converters for stepping down the voltage from the phase transmission voltage of 360V to distribution voltage of 48V. The factors considered are primarily maximum output power, the output current and input voltage. Assuming 26 houses and a peak load of 39kW gives each house a maximum power consumption of 1500W. At 48V the load side current would thus be around 31A per house. The component chosen was a converter from Scheafer Power, the *C4589G*. Which has a top efficiency of 92% according to the data sheet. It has an input voltage of 320-640V and a maximum output current of 30A. It has an output voltage of 48V but a range of

45-55V. So the maximum load per converter could be 1650W, but aiming for 48V the maximum load per house would be capped at 1440W.

4.6.5 Cables

For cable dimensioning using equations 3.1 and 3.4 again. Starting out with the PV cable, assuming a maximum possible production of 86kWp and a nominal phase voltage of 720V would give the maximum possible current in the cable as 119A. At minimum this would require a cross-section of $35mm^2$ according to B.1. At 100m and trying to aim for a maximum transmission loss of 5%, if using $35mm^2$ that would give a maximum loss of 2.61%. For transmission assuming a maximum load of 38.9kW at 720V would give the maximum current as 55A. Three different cable cross sections will again be tested and those will be $10mm^2$, $16mm^2$ and $25mm^2$. With $10mm^2$ being the default value if nothing else is mentioned. The reason they are chosen is simply that the load is now higher and a step up of bigger cables is taken in compared to the current scenario. For distribution a 50m cable will be used and if each of the four house groups, has a maximum load of 38.9/4=9.72W that would give a maximum current of 27A. Again aiming for maximum loss of 5%, $6mm^2$ cable gives 2.1% losses and will be tested.

4.6.6 Grid protection

As in Design A, breakers and grid protection is suggested in chapter 6.4.3 after simulation of short circuit currents.

4.6.7 Summary

In summary what will be tested in design B are:

- 85.5kWp TATA Solar 285W Panel
- $35mm^2$ PV cable
- $10mm^2/16mm^2/25mm^2$ 3-phase cable for transmission
- $6mm^2$ distribution cable
- 12PVB121 Lithium-ion batteries
- 1420W 30A Scheafer DC/DC converter

Chapter 5

Models and simulation

Modelling and simulation of the micro grid is split into two different ones. One model is built for looking at the two designs in steady state, mainly losses and efficiency. The second model is built looking at short circuit currents and how high they are during different faults. Both have been built from scratch with components found in Simulink.

5.1 Simulation software - Matlab with Simulink

The software used for modelling and simulation have been Matlab 2016b in combination with Simulink. In Simulink the Simscape Power systems environment was used. Matlab and simulink was provided by Lund University faculty of engineering and used with a student license.

5.2 Input data

Input data for the models are divided into production data and load data.

5.2.1 Production data

Production data is the amount of energy produced. In this case because the only source of input is solar PV, the production data is thus solar radiation over time in W/m^2.

- For the steady state model it is based on solar radiation data collected on 29 april 2007, to represent an average sunny day in the Andaman Islands.

5.2.2 Load data

The load data is divided into four profiles, 2 for design A and 2 for design B.

For design A:

- The first profile is the scaled residential profile with a scaling factor of 8.52 as seen in 4.8
- The second is a load profile used for short circuit current analysis of design A. It takes the peak load value that Homer gave us of 17.82 kW

For design B:

- The third profile is the scaled residential profile for a future load scenario that design B is based on. It uses the residential profile with a scaling factor of 18.5 as seen in 4.9
- The fourth is a load profile for the short circuit analysis of design B and uses the peak load that Homer gave us of 38.9kW

5.3 Micro grid steady state model

The steady state model is the model designed to look at the system over longer periods of time. This has been used to look at the grid energy efficiency and losses. Much of the components used are ready built in the simscape environment for this kind of purpose.

5.3.1 Overview

The basic layout follows the Teroc proposal we showed in figure 4.5 as closely as possible. An overview of the model can be seen below inside the Simulink environment.

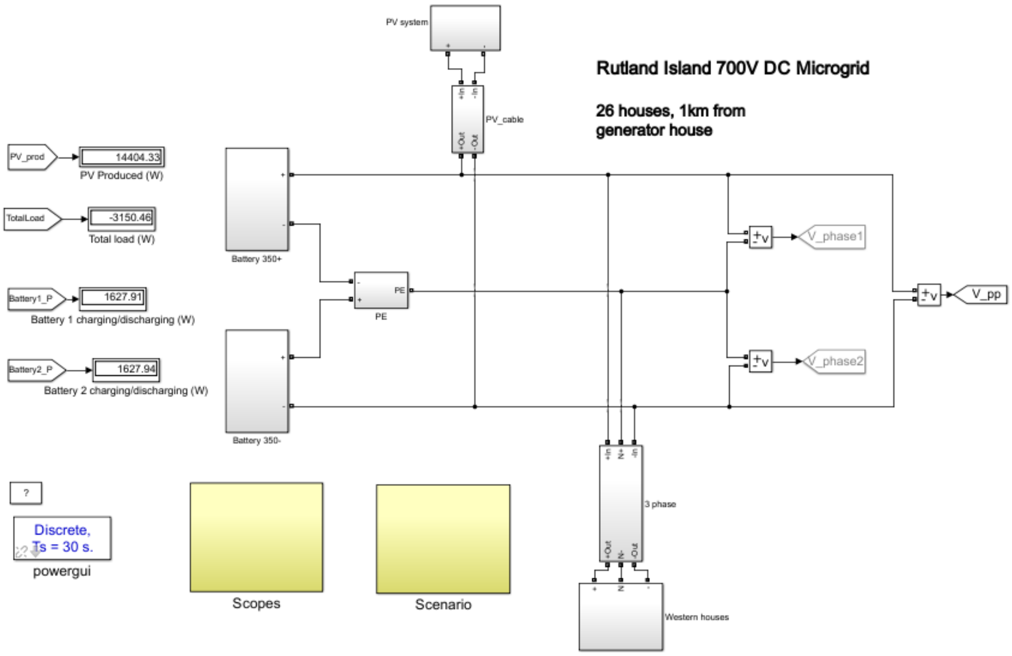


Figure 5.1: Steady state model

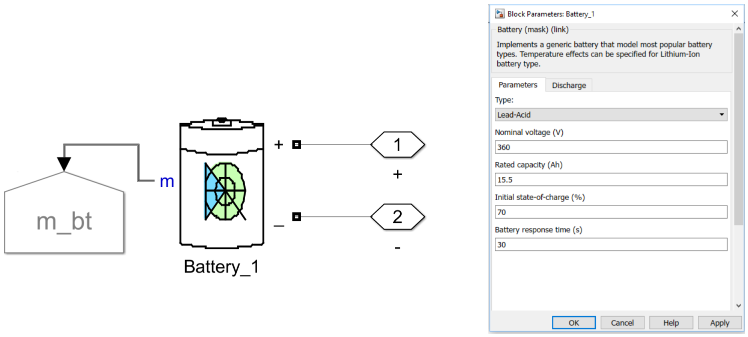
Simulation time is set to 24h or 86400s, with discrete time steps of 30s. The solver used is ode23t.

5.3.2 Design parameters

The way to set the model to a specific design, A or B, is done by running Matlab scripts outside of the Simulink model. It sets solar PV parameters, battery parameters, Power electronic converter parameters and cable parameters.

5.3.3 Batteries

The two battery banks are modelled with the Simscape power systems battery component. It is described in detail at the MathWorks website [30]. It is modelled so that it includes the battery charger and can both be charged and discharged. At the end they conclude that it has an error margin of +/- 5% compared to a real battery.



Battery (mask) (link)

Implements a generic battery that model most popular battery types. Temperature effects can be specified for Lithium-Ion battery type.

Type: Lead-Acid

Nominal voltage (V): 360

Rated capacity (Ah): 15.5

Initial state-of-charge (%): 70

Battery response time (s): 30

Figure 5.2: Model of the system battery bank with battery bank parameters to the right

It has the option of switching between different battery types (for example Lithium-ion and Lead Acid) and setting battery parameters like nominal voltage, rated capacity and initial state of charge. The discharge parameters are by default calculated from the other parameters.

5.3.4 PV array

The solar PV is modelled with the Simscape power systems PV array component. As the batteries above a full description can be found on the MathWorks website [31].

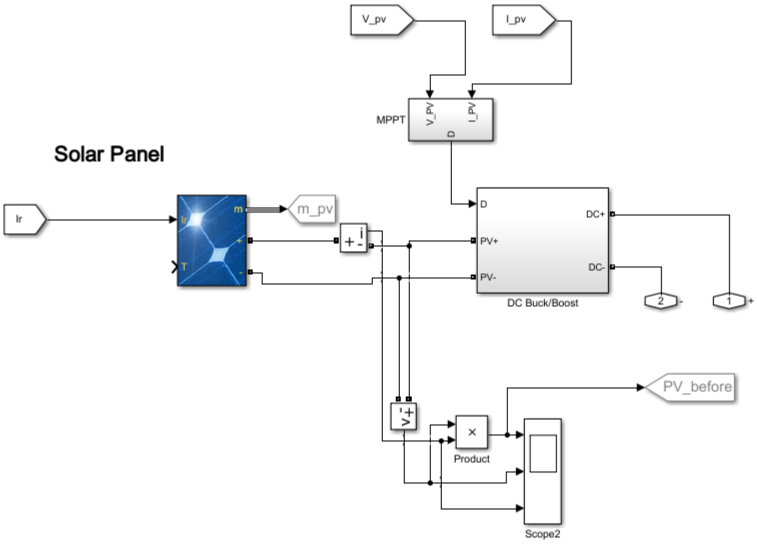
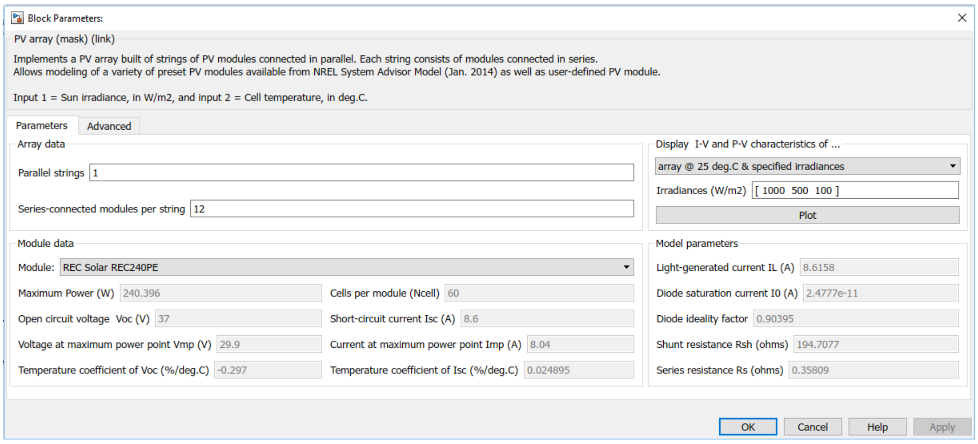


Figure 5.3: Overview of the model PV system

It has the option of choosing between preset PV modules from the NREL System Advisory Model database and their characteristics. The inputs are irradiance in W/m^2 and temperature in deg. C. In this thesis, temperature as a factor has been omitted due to lack of temperature data.



PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Array data

Parallel strings: 1
Series-connected modules per string: 12

Display I-V and P-V characteristics of ...: array @ 25 deg.C & specified irradiances
Irradiances (W/m2): [1000 500 100]

Module data

Module: REC Solar REC240PE
Maximum Power (W): 240.396
Cells per module (Ncell): 60
Open circuit voltage Voc (V): 37
Short-circuit current Isc (A): 8.6
Voltage at maximum power point Vmp (V): 29.9
Current at maximum power point Imp (A): 8.04
Temperature coefficient of Voc (%/deg.C): -0.297
Temperature coefficient of Isc (%/deg.C): 0.024895

Model parameters

Light-generated current IL (A): 8.6158
Diode saturation current I0 (A): 2.4777e-11
Diode ideality factor: 0.90395
Shunt resistance Rsh (ohms): 194.7077
Series resistance Rs (ohms): 0.35809

Figure 5.4: An overview of PV module options

Each string in the PV array is connected to a ferroAmp Solar String Optimizer. This is modelled with a single average boost converter component, controlled by a maximum power point tracker script. The MPPT script is a Perturb and Observe algorithm based on code from the Matlab example "400-kW Grid-Connected PV Farm".

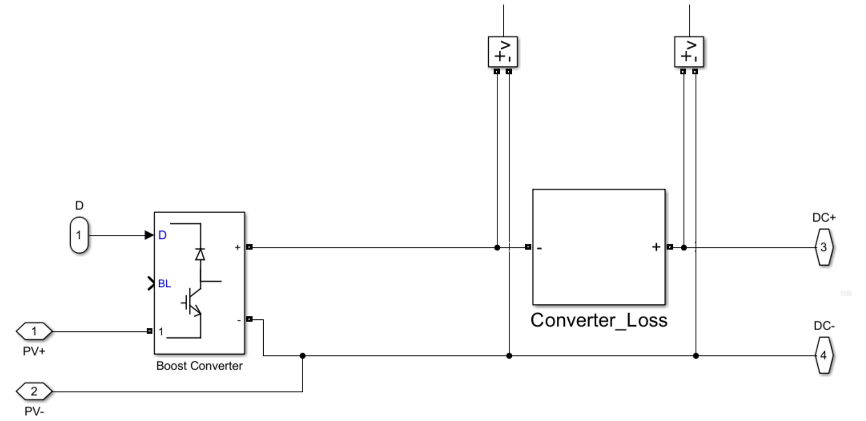


Figure 5.5: The PV DC/DC Converter

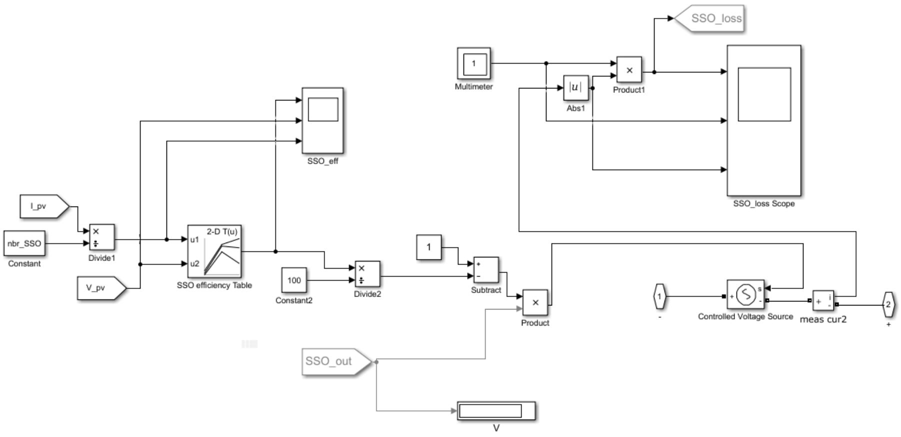


Figure 5.6: Solar String optimizer losses

Because the boost converter component is ideal a subsystem to add the correct losses is added in series. This is done by using an efficiency lookup table with the data provided by FerroAmp themselves. It takes the output voltage and output current from the PV array, looks up the efficiency and then subtracks a % from the converter output power.

5.3.5 Cables

As we mentioned when dimensioning the grid three different cables have been used and thus modelled.

All the cables are modelled as a pure lumped resistive element for each phase and neutral respectively. So for the 700V transmission cable between the generator house and the western settlement there is one resistance on each wire representing a distance of 1000m as seen below.

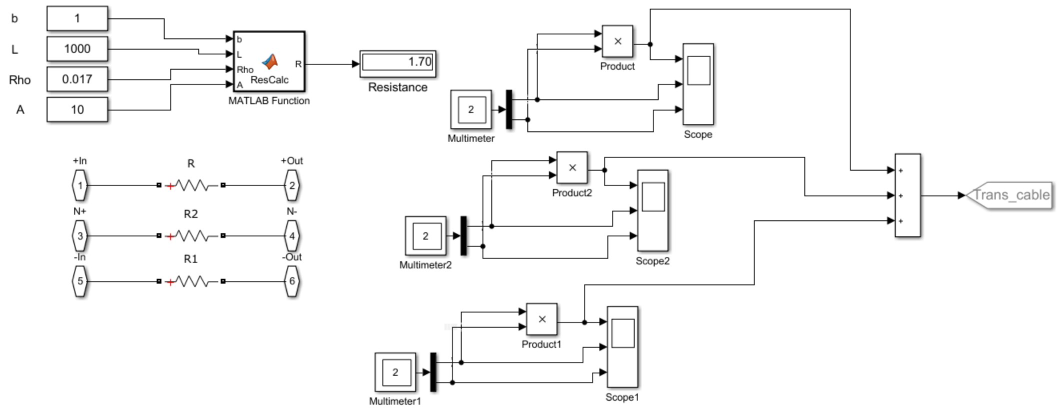


Figure 5.7: 2 phase + neutral - transmission cable

The same method is used for the PV transmission cable and the distribution cables respectively.

5.3.6 Loads

The loads in the system is the 26 houses that was mentioned previously. They are split into 26 individual units and split evenly between the phases, 13 on each 350V phase. The 13 houses are grouped into 2 groups of 6 and 7 houses each.

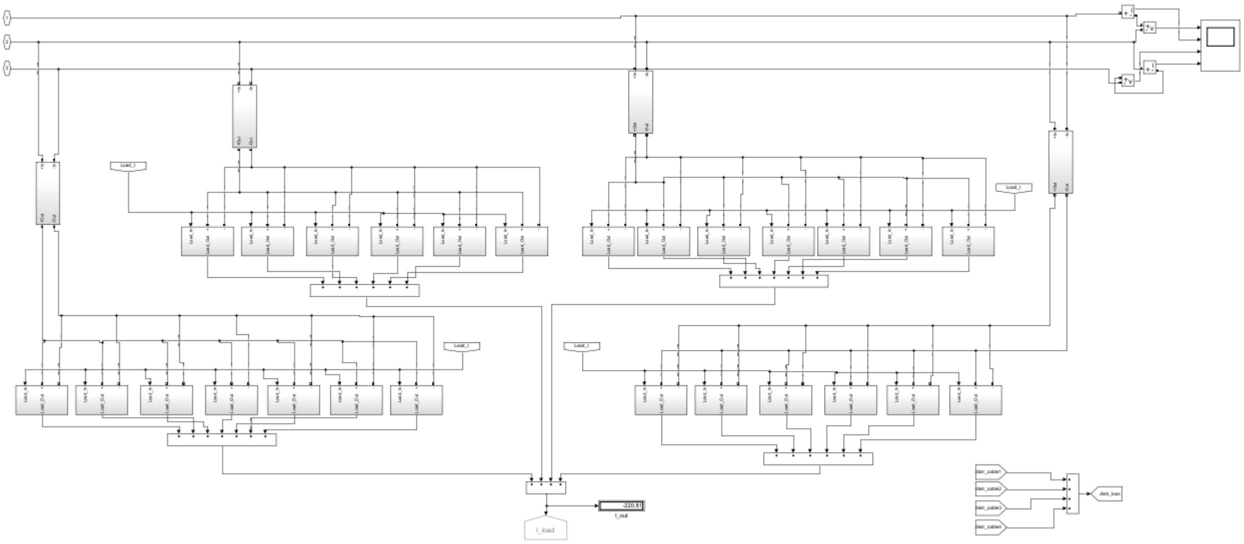


Figure 5.8: Houses

Each house consists of a DC/DC converter and a load. The load has an input of how much current it should draw at 48V. With the input coming from the scenario tab (described below) and a lookup table of the previously mentioned load input data.

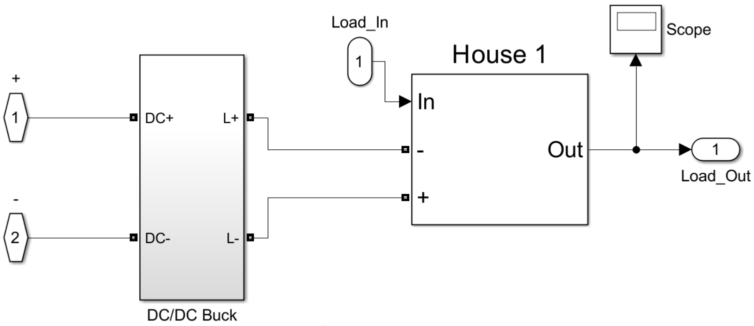


Figure 5.9: Inside the house

Below is an overview of how the houses are constructed. A current source with a snubber in parallel and in series with a resistive load. Making it similar to a variable resistor controlling the current through the load. The idea comes from the Simulink simscape power systems example "Power microgrids".

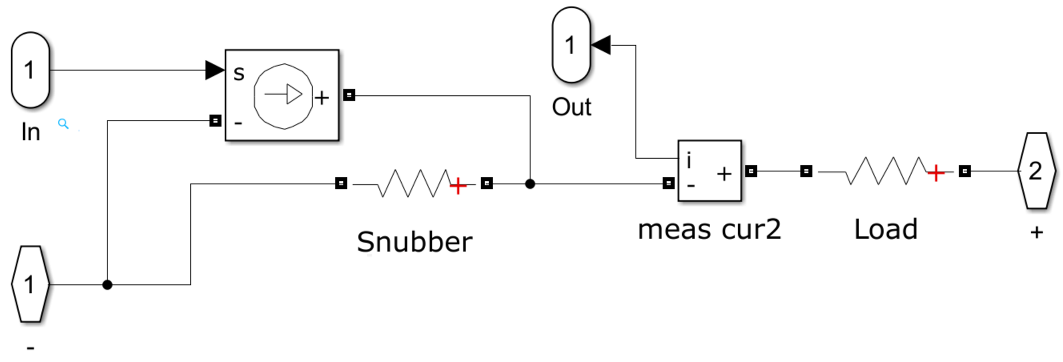


Figure 5.10: How the load inside the house works

5.3.7 350V/48V Power electronics

The DC/DC converter for converting from the phase voltage of 350V to distribution voltage of 48V is modelled with the built in Simscape DC/DC converter. It gives you the option of setting maximum converter efficiency, maximum allowed output current and maximum converter output power.

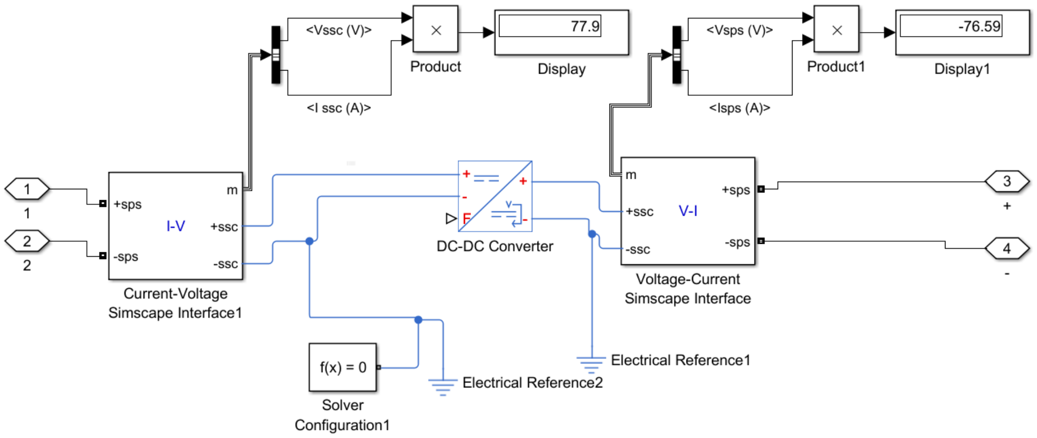


Figure 5.11: House DC/DC converter

No efficiency curves (like the one obtained from FerroAmp for their SSO) was at the time of writing available from neither FEAS or Schaefer for the respective converters, only maximum efficiency numbers. So the simscape DC/DC converter has been used and the maximum efficiency numbers, mentioned in dimensioning of A and B, which was obtained from their respective data sheets have been input. The losses in the power electronics can be related to the theory in 3.6.2, which is what the numbers in the data sheets are based on.

5.3.8 Data input

The scenario subsystem is where the production data and load data is input. 2D lookup tables are used with the data mentioned in Input data and and sent on to the PV array and loads respectively.

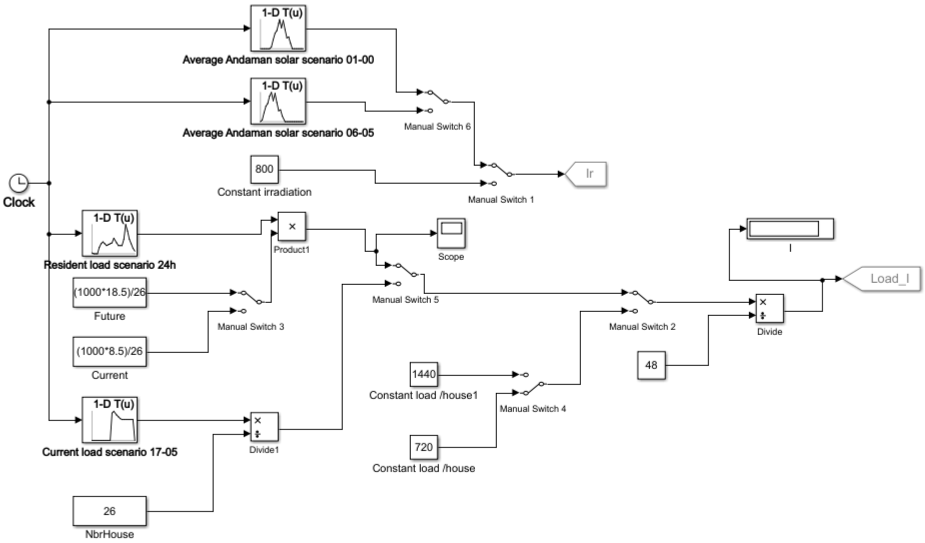


Figure 5.12: Scenario subsystem

5.4 Micro grid short circuit current model

The second model is designed for looking at short circuit currents (Isc) in the system at different points. It is an average model and designed to give an approximation of the peak and steady state Isc, on an accuracy level of the IEC 61660-1 standard. The model consists of a battery (in bipolar configuration), transmission cables, distribution cables and loads.

The theory behind the model is based on the ABB document on breakers and short circuit currents, in combination with the IEC 61660-1 standard. To summarize this states that in our case the two possible components contributing to the Isc in a LVDC system is batteries and smoothing capacitors. Batteries are included in the model but the smoothing capacitors are not. The possible source for smoothing capacitors in our system would be the DC/DC converters, but after looking through the data sheets it was concluded that they have short circuit current protection and thus should not contribute.

5.4.1 Overview

An overview of the model can be seen below. It omits the PV array all together. The reason for this is because of its isolation from the grid with a DC/DC converter, which we said above did not contribute.

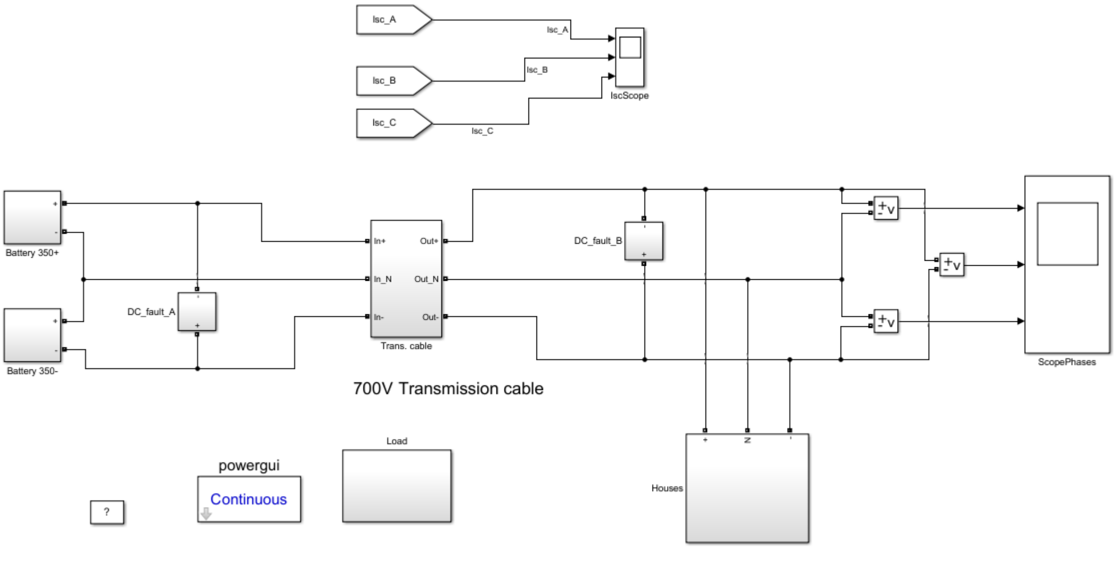


Figure 5.13: Model for determining Isc - short circuits in the system

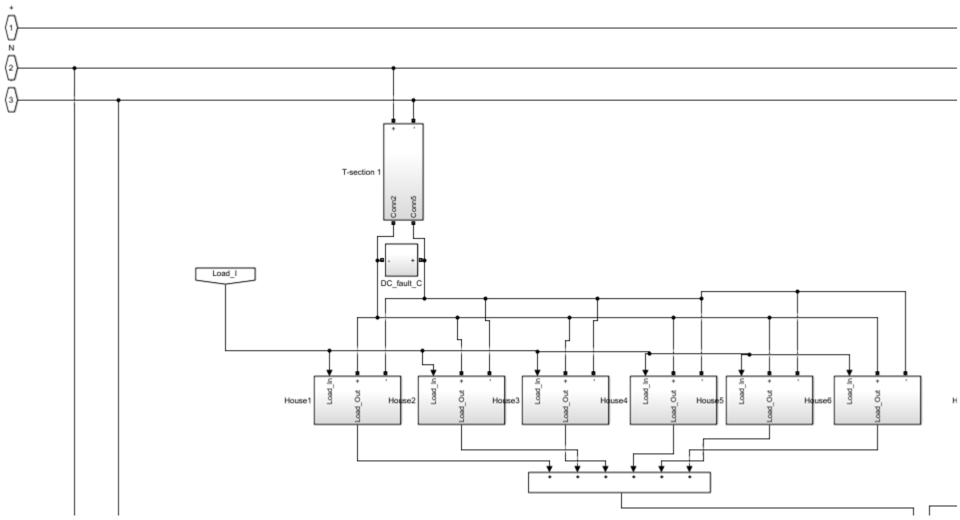


Figure 5.14: Fault C at distribution level

5.4.2 Batteries

For modelling the batteries both Lead-acid and Lithium-ion have been modelled the same way when it comes to short circuit currents. There is a debate and research going on if you can do this or if Lithium-ion batteries should be modelled in a different way. But for this thesis we have chosen to do it.

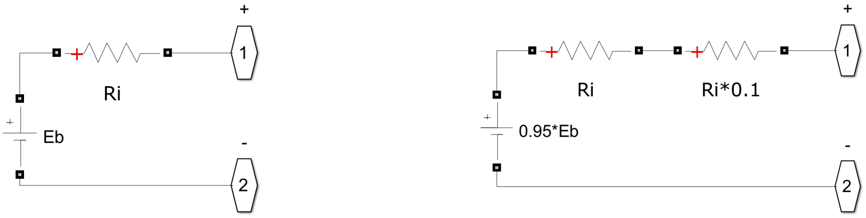


Figure 5.15: To the left a battery for peak short circuit current and to the right a battery for steady state short circuit current

Because both peak Isc (Ipb) and steady state Isc (Ikb) is interesting for determining breaker sizes, two ways have been used to model the batteries.

For Ipb the battery has been modelled as an ideal voltage source Eb in series with the internal resistance Ri of the battery according to equation 3.7, $ipb = \frac{Eb}{R}$. Eb is the fully charged voltage of the battery, so in the model the source voltage is set to equal what the voltage would be at 100% SOC.

For Ikb, equation 3.8 have been used, $ikb = \frac{0.95*Eb}{R+0.1*Rb}$. The Isc contribution from batteries are now 95% of the fully charged voltage and R + 10% of Ri. So an second resistance have been added in series with Eb and Ri, equalling 10% of Ri.

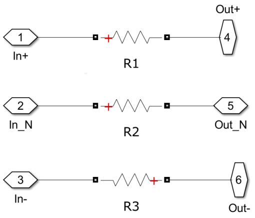


Figure 5.16: Transmission cable

5.4.3 Cables

All transmission cables and distribution cables are modelled as purely resistive elements because of the short length of cables.

5.4.4 Loads

The loads are modelled in the same way as in the steady state model with a current source, a snubber in parallel and in series a resistance.

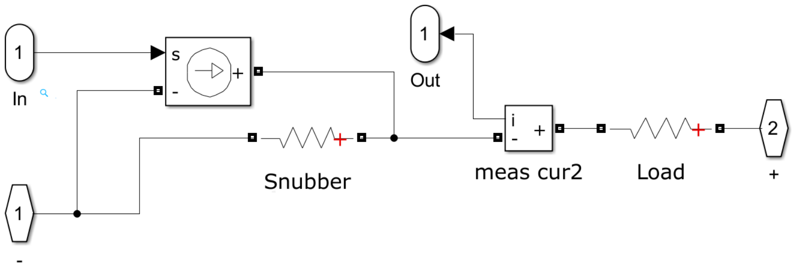


Figure 5.17: How the load inside the house works

5.4.5 Faults

Three different faults locations are included as seen in figure 5.13 and 5.14.

- DC fault A - A short circuit at the battery
- DC fault B - A short circuit at transmission level
- DC fault C - A short circuit at distribution level

The faults have been modelled as a switch with a fault impedance set to 1e-10Ω, to get a close to zero impedance fault. When the switch is turned on it simulates a short circuit giving rise to an short circuit at that point in the system.

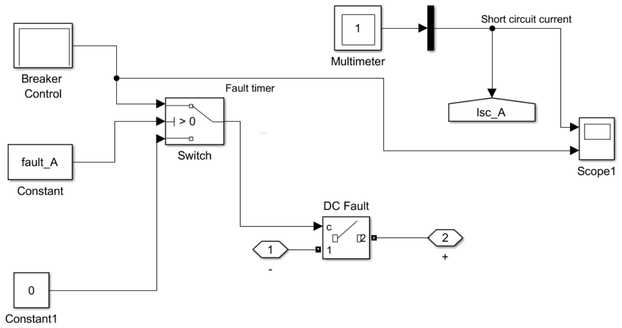


Figure 5.18: Inside the fault

Chapter 6

Simulation results

In this chapter the simulation results will be presented. They are divided into sections for a system overview, losses, energy efficiency and short circuit currents with subsections in each for Design A and B.

A comment on the results will be included in each subsection and then a summary and discussion of all the results follow at the end.

6.1 Power balance

Looking at an overview of both designs over 24h. The power produced by the solar PV, the total load, the total losses, battery power, battery state of charge and time of day.

- All simulation was done with the batteries starting at 50% state of charge.
- Simulation time is 24h with the lowest graph showing hour of the day.
- Battery power and battery SOC respectively should be two lines in each graph, but because the load on each phase is equal, they overlap and no difference can be seen in the graph below.

6.1.1 Design A

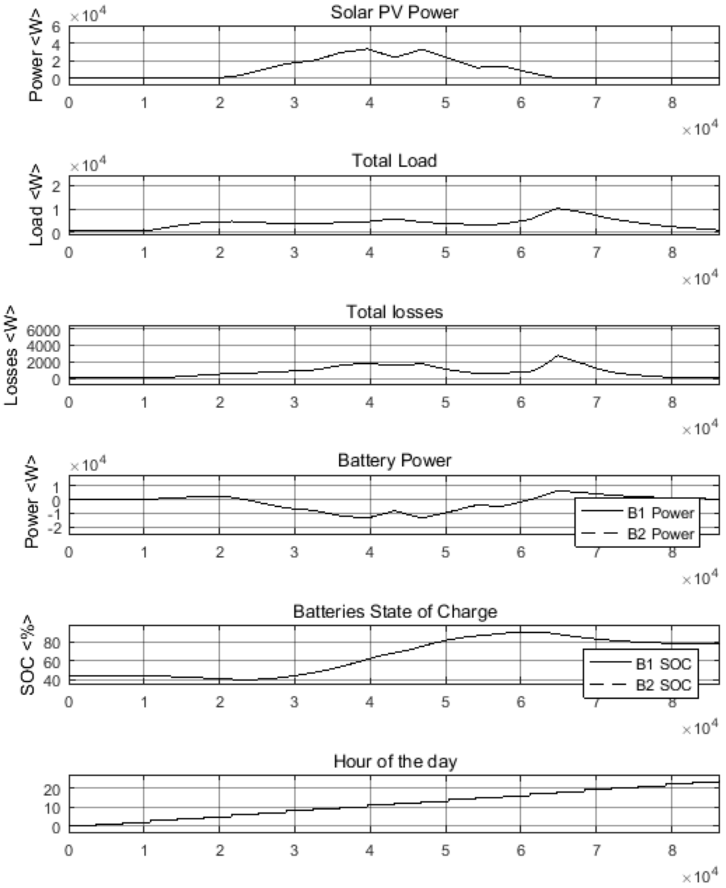


Figure 6.1: Overview of design A with 6mm^2 transmission cable

Looking at an overview of Design A. We can see that with the current irradiation profile, we get around a peak of 32kW output from the PV array out of 37kWp possible. The load peaks at 11kW, which is lower then the 17.9kW Design A was designed for. The batteries reach a peak SOC of around 80%. We can see roughly just by looking at the graph that the power balance in the system works out. By calculating the sum of solar PV Power + load + losses + battery power = 0, which means that the system works as intended. But we can also see that the batteries will be quickly fully charged in 2-3 days if left as it is already reaching 80% SOC the first day.

6.1.2 Design B

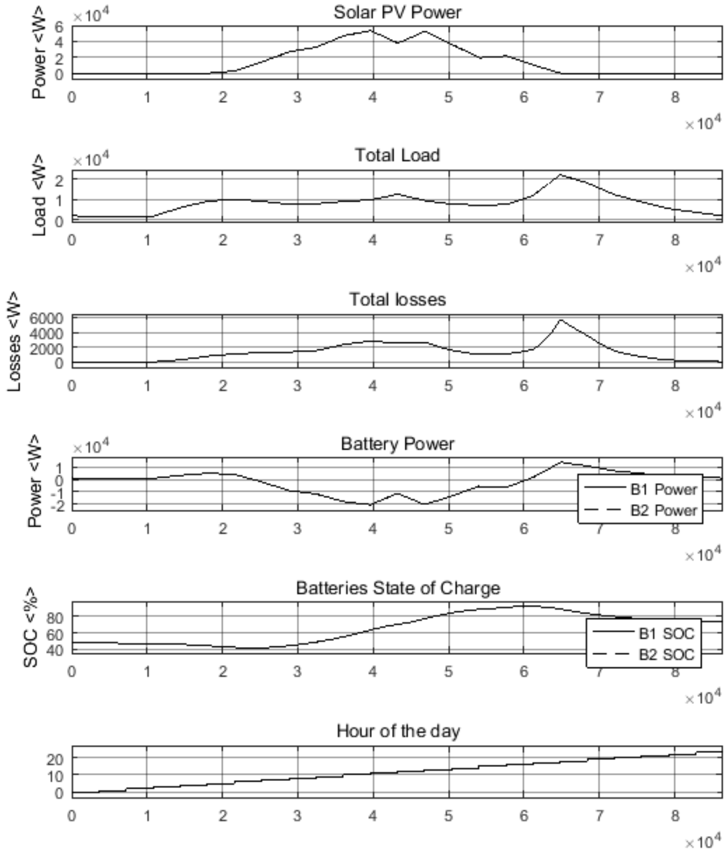


Figure 6.2: Overview of design B with 10mm^2 transmission cable

We can see that with the current irradiation profile we get around 56kW maximum output from the PV array out of 86kWp. The maximum load is around 22kW, which is lower then the 39kW, that the system was originally designed for. The batteries reach a peak SOC of around 80% again. The same can be said as above, with the power balance checking out and that the battery dimensioning needs to be investigated otherwise the batteries would be quickly fully charged.

6.2 Losses

Looking at system losses, they will be given for each component contributing in kWh, for the whole period of 24h. As previously stated, no losses in the batteries are counted or assumed.

The losses in the system comes from five sources:

- 700V transmission cables - All the losses in transmission from the generator house to the western settlement
- PV transmission cables - The losses in transmission from the PV panels to the main grid.
- Distribution cables - all the cables which connects the houses to the main grid lumped together as one total loss.
- 350/48V Power electronics - The losses in the 26 DC/DC converters which convert the voltage from transmission voltage to distribution voltage.
- PV power electronics - The total losses in the FerroAmp SSOs that are used, they are all lumped together as one number.

6.2.1 Design A

For design A, looking at losses. Simulations have been done for each of the three different cross-sections tested, $6mm^2/10mm^2/16mm^2$.

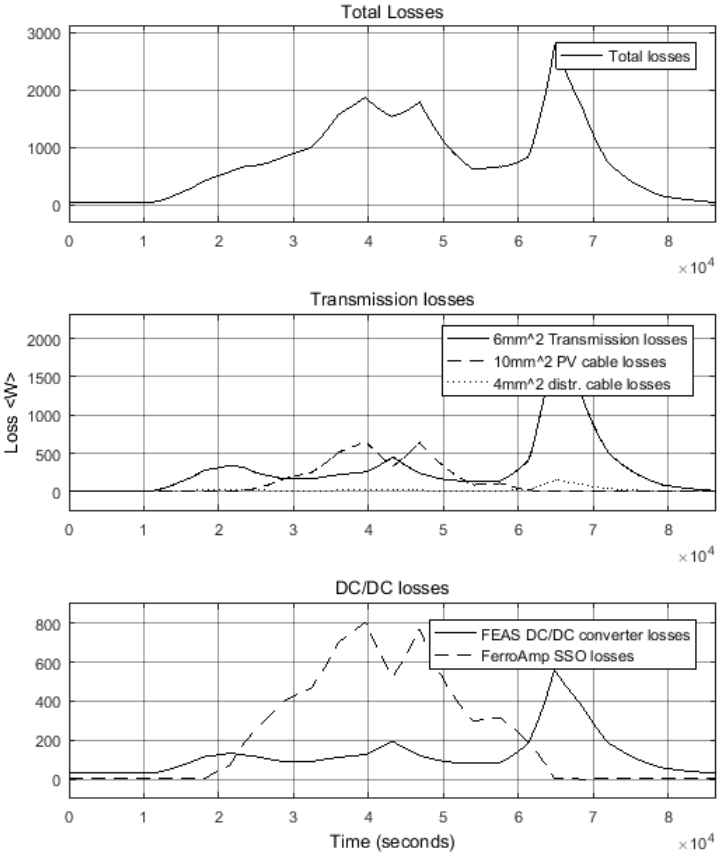


Figure 6.3: Average losses during 24h with $6mm^2$ transmission cable

The losses for the design with $6mm^2$ cross section are 7.3kWh lost in 700V transmission, 3kWh in PV transmission, 0.55kWh in distribution, 2.99kWh in 350/48V Power electronics and 5.29kWh in PV power electronics. In total around 19.2kWh in losses over 24h. A note is that the peak for transmission losses in the middle graph is concealed by the info window, but peak number is 2kW.

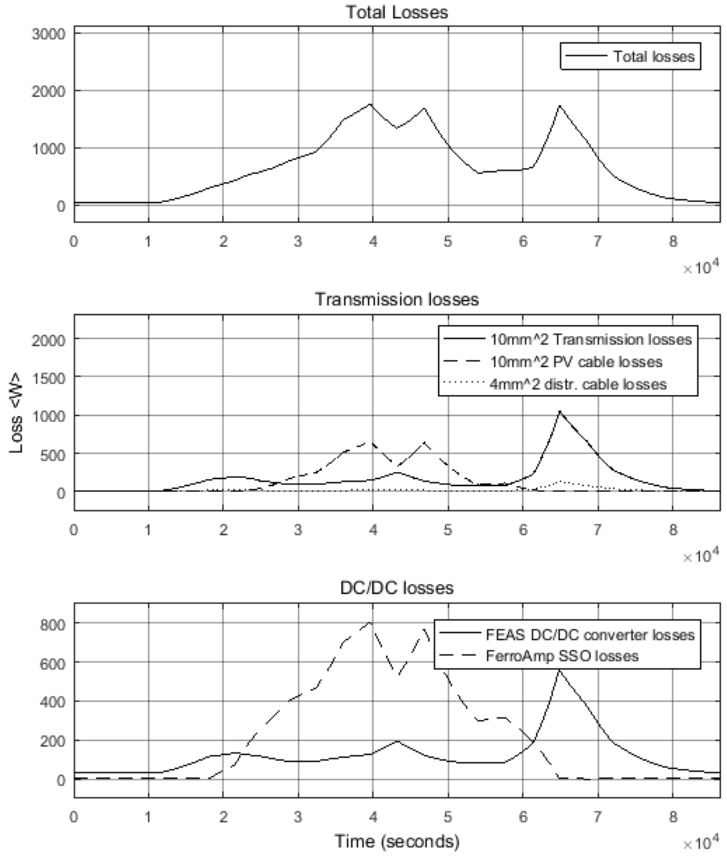


Figure 6.4: Average losses during 24h with $10mm^2$ transmission cable

The losses for the design with $10mm^2$ cross section are 4kWh lost in 700V transmission, 3kWh in PV transmission, 0.5kWh in distribution, 2.99kWh in 350/48V Power electronics and 5.3kWh in PV power electronics. In total around 15.9kWh in losses over 24h.

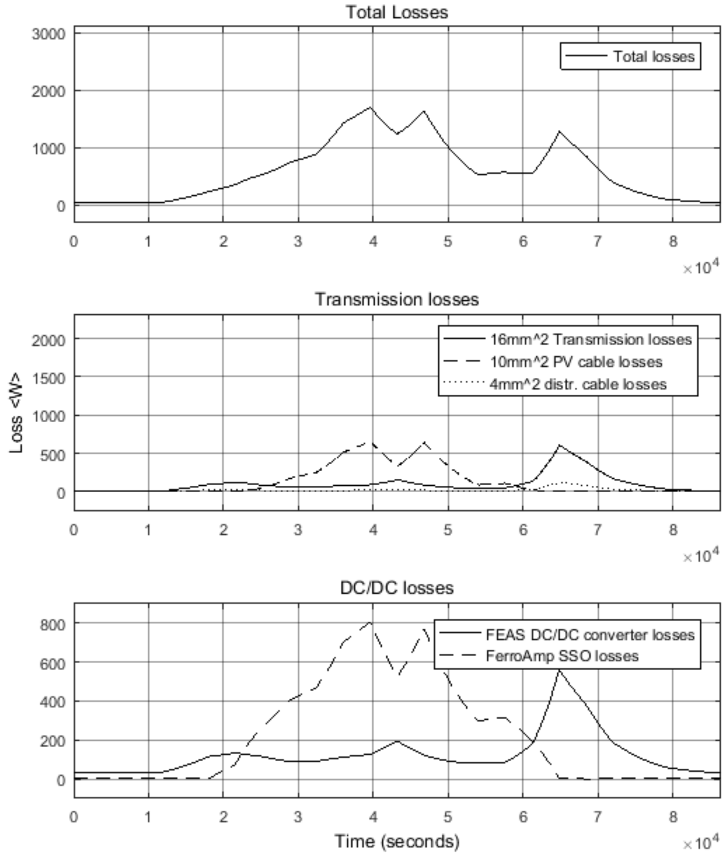


Figure 6.5: Average losses during 24h with $16mm^2$ transmission cable

The losses for the design with $16mm^2$ cross section are 2.4kWh lost in 700V transmission, 3kWh in PV transmission, 0.48kWh in distribution, 2.99kWh in 350/48V Power electronics and 5.3kWh in PV power electronics. In total around 14.24kWh in losses over 24h.

6.2.2 Design B

For design B looking at losses. For average load the losses for the three different cross section of transmission cable are:

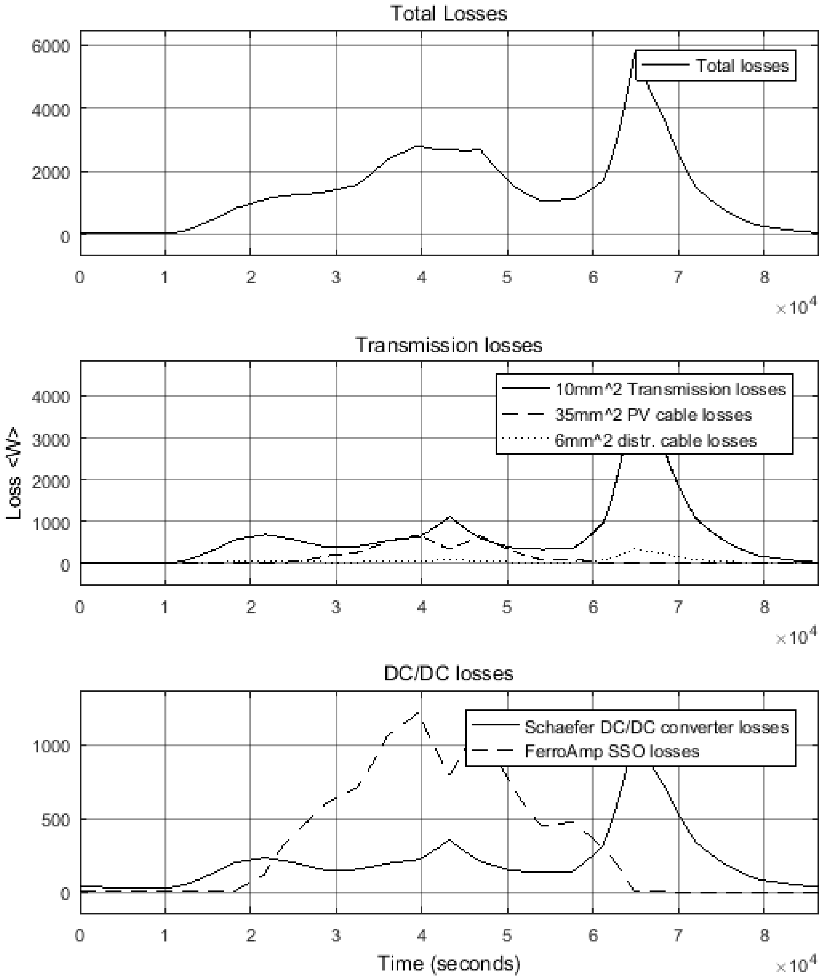


Figure 6.6: Average losses during 24h with $10mm^2$ copper transmission cable

The losses for design B with $10mm^2$ cross section are 16.2kWh lost in 700V transmission, 3.2kWh in PV transmission, 1.36kWh in distribution, 5.24kWh in 350/48V Power electronics and 8kWh in PV power electronics. In total around 34kWh in losses over 24h.

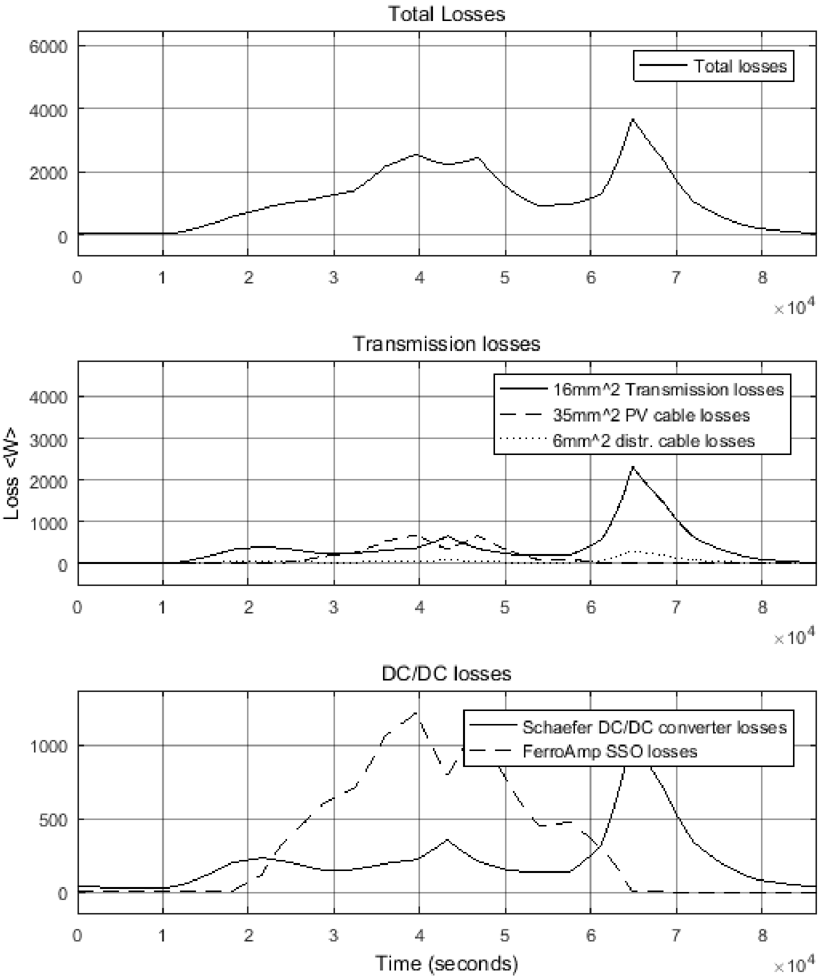


Figure 6.7: Average losses during 24h with $16mm^2$ copper transmission cable

The losses for design B with $16mm^2$ cross section are 9.3kWh lost in 700V transmission, 3.2kWh in PV transmission, 1.25kWh in distribution, 5.24kWh in 350/48V Power electronics and 8kWh in PV power electronics. In total around 27kWh in losses over 24h.

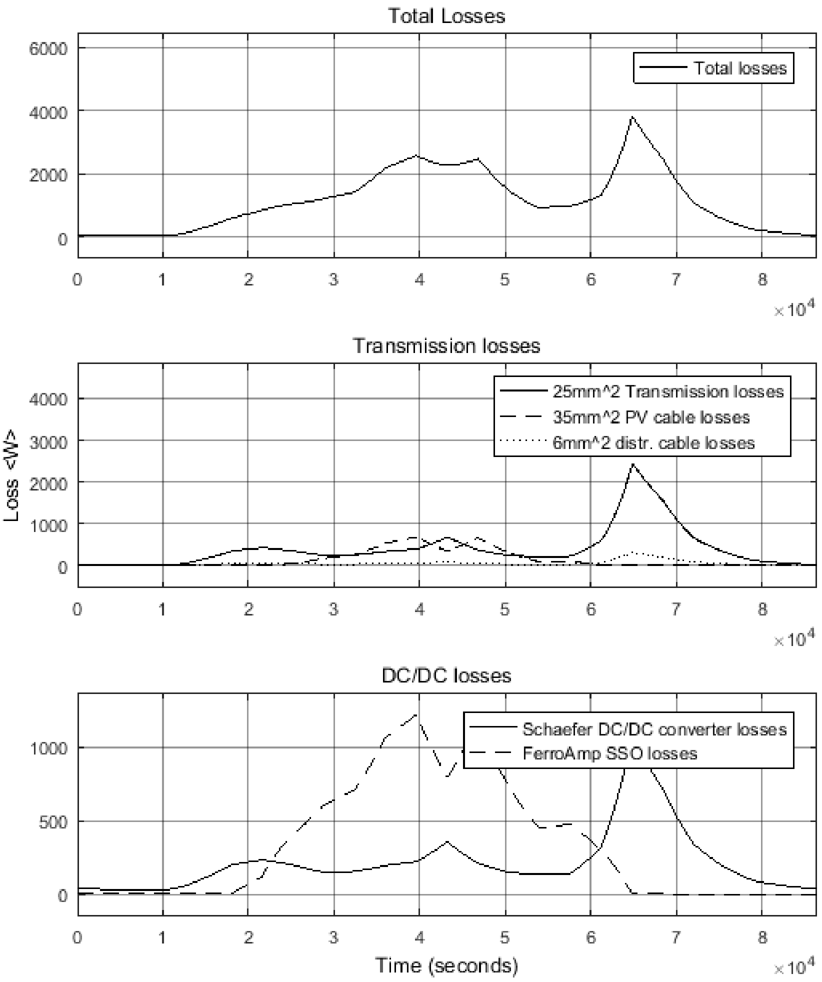


Figure 6.8: Average losses during 24h with $25mm^2$ aluminium transmission cable

The losses for design B with $25mm^2$ cross section are 9.78kWh lost in 700V transmission, 3.2kWh in PV transmission, 1.25kWh in distribution, 5.24kWh in 350/48V Power electronics and 8kWh in PV power electronics. In total around 27.5kWh in losses over 24h.

6.3 Energy efficiency

Moving on to energy efficiency. Here the amount of energy put into the system at a given point will be compared to the amount of energy consumed at the same point and give a total system energy efficiency. Depending on if the battery at a given point is either producing or consuming energy it will either be counted with total load or together with the PV produced.

Looking at the three different cross sections of transmission cable again. Energy efficiency will be measured on average and at two points in time, at maximum load and at maximum PV output. Chosen because these are the two factors contributing to the highest losses and to get the worst case scenario.

6.3.1 Design A

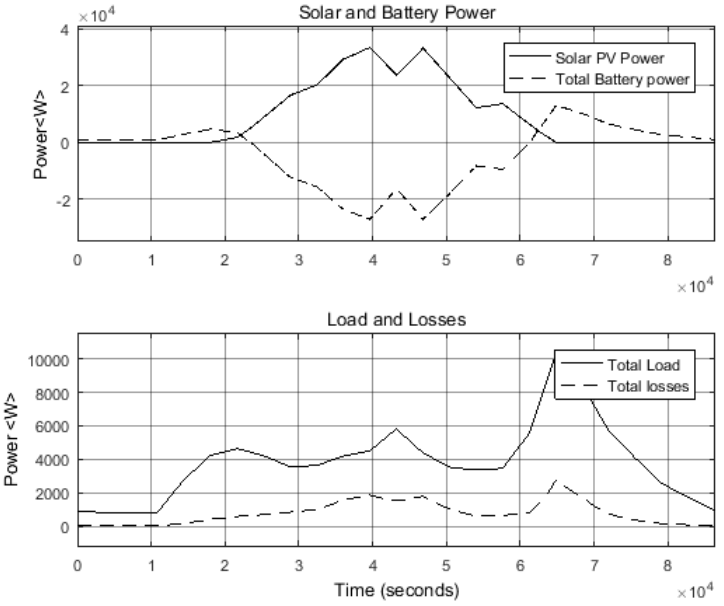


Figure 6.9: Energy produced, battery power, load power and losses during 24h with $6mm^2$ transmission cable

The total amount of energy produced during 24h is here 221.3kWh and the total losses are 19.2kWh. The average efficiency is thus, $1-(\frac{19.2}{221.3}) = 0.913 = 91.3\%$.

For the design with $6mm^2$ transmission cable the efficiency is:

- 78.9% at maximum load. With 13.022kW put in and 10.28kW taken out.
- 94.4% at maximum PV output. With 33.3kW put in and 31.53kW taken out.

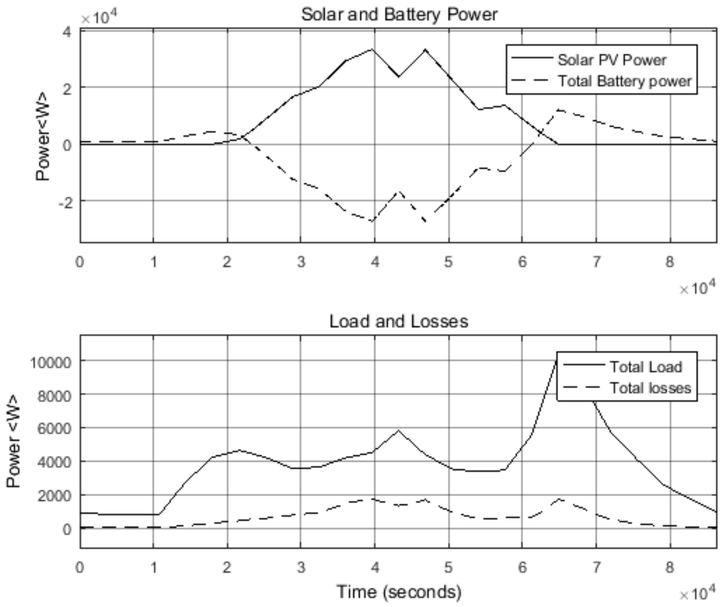


Figure 6.10: Energy produced, battery power, load power and losses during 24h with $10mm^2$ transmission cable

The total amount of energy produced during 24h is here 221.3kWh and the total losses are 15.88kWh. The average efficiency is thus, $1 - (\frac{15.88}{223.4}) = 0.928 = 92.8\%$.

For the design with $10mm^2$ transmission cable the efficiency is:

- 85.5% at maximum load. With 12kW energy put in and 10.28kW energy taken out.
- 94.77% at maximum PV output. With 33.8kW put in and 31515kW taken out.

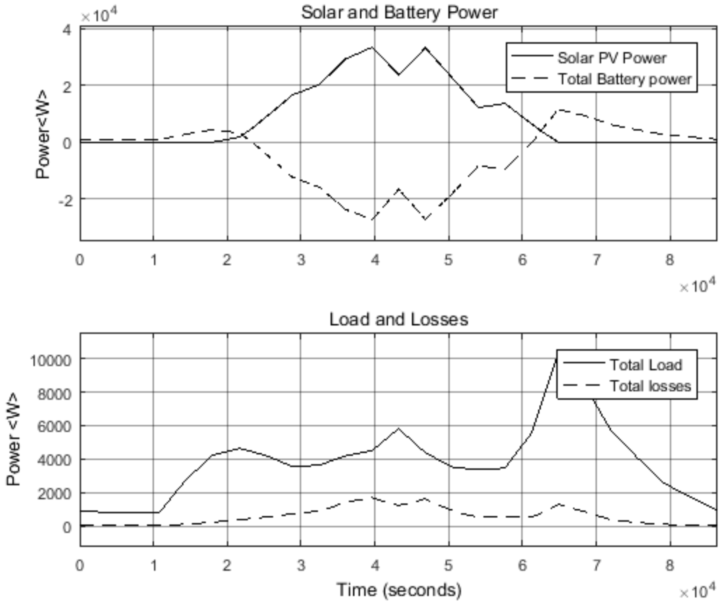


Figure 6.11: Energy produced, battery power, load power and losses during 24h with $16mm^2$ transmission cable

The total amount of energy produced during 24h is here 221.3kWh and the total losses are 14.25kWh. The average efficiency is thus, $1 - (\frac{14.25}{221.4}) = 0.9356 = 93.56\%$.

For the design with $16mm^2$ transmission cable the efficiency is:

- 88.98% at maximum load. With 11.55kW energy put in and 10.28kW energy taken out.
- 94.94% at maximum PV output. With 33.34W put in and 31.71kW taken out.

6.3.2 Design B

Below is the three cross-sections for design B.

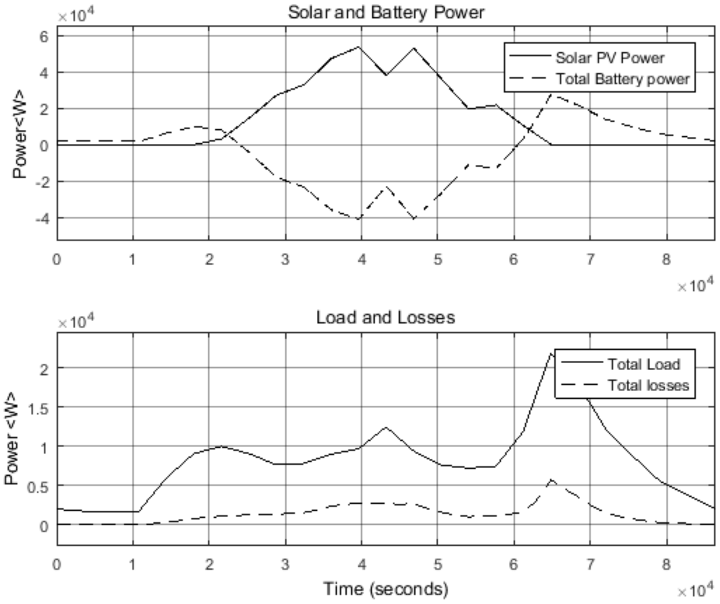


Figure 6.12: Energy produced, battery power, load power and losses during 24h with $10mm^2$ transmission cable

The total amount of energy produced during 24h is here 356.7kWh and the total losses are 34kWh. The average efficiency is thus, $1-(\frac{34}{356.7})=0.9047=90.47\%$.

For design B with $10mm^2$ transmission cable the efficiency is:

- 79.47% at maximum load. With 27.566kW put in and 21.9kW taken out.
- 94.7% at maximum PV output. With 53.6kW put in and 50.8kW taken out.

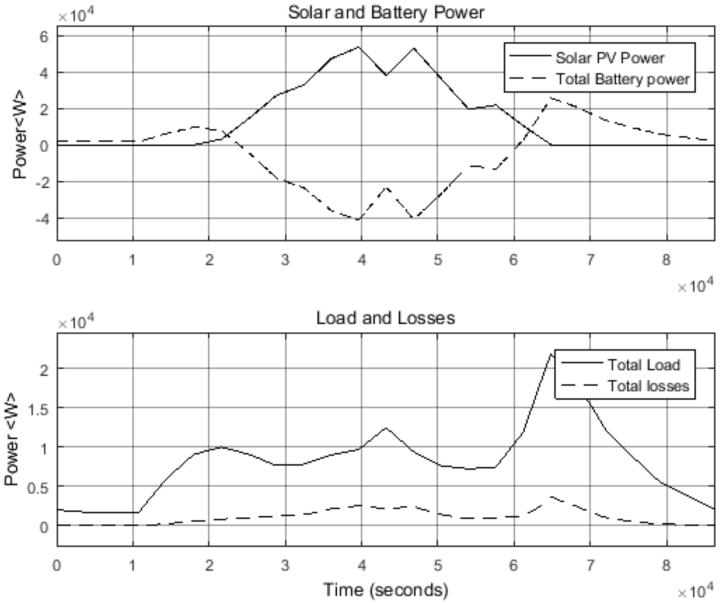


Figure 6.13: Energy produced, battery power, load power and losses during 24h with $16mm^2$ transmission cable

The total amount of energy produced during 24h is here 356.7kWh and the total losses are 27kWh. The average efficiency is thus, $1 - (\frac{27}{356.7}) = 0.924 = 92.4\%$.

For design B with $16mm^2$ transmission cable the efficiency is:

- 85.7% at maximum load. With 25.53kW put in and 21.9kW taken out.
- 95.25% at maximum PV output. With 53.6kW put in and 51kW taken out.

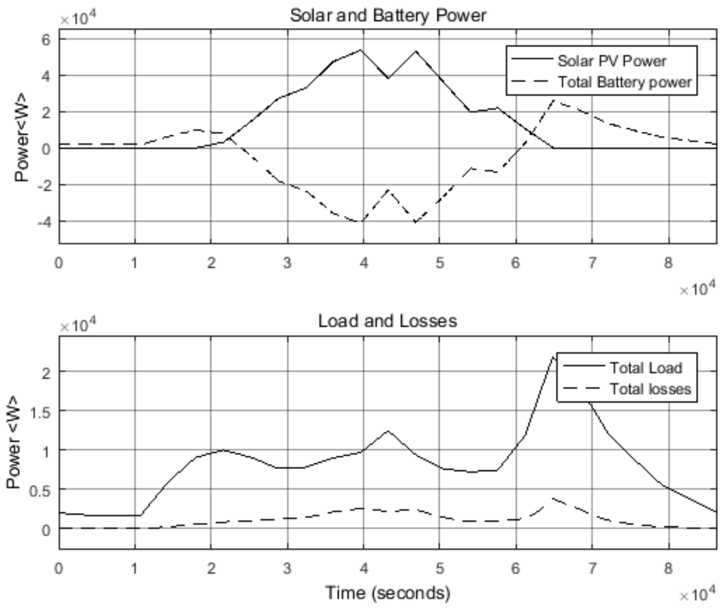


Figure 6.14: Energy produced, battery power, load power and losses during 24h with $25mm^2$ transmission cable

The total amount of energy produced during 24h is here 356.7kWh and the total losses are 27.5kWh. The average efficiency is thus, $1 - (\frac{27.5}{356.7}) = 0.9229 = 92.29\%$.

For design B with $25mm^2$ transmission cable the efficiency is:

- 85.36% at maximum load. With 25.663kW put in and 21.907kW taken out.
- 95.22% at maximum PV output. With 53.6kW put in and 51kW taken out.

6.4 Short circuit currents

Looking at the safety aspects and short circuit currents (Isc). First an analysis with the same cable sizes as previously are done in regards to short circuit currents. The three points mentioned in modelling have been tested. Only phase to phase faults are tested because of what ABB concluded in their review on DC faults. This will be followed by a comparison at each respective level to test if the cables chosen can handle the peak Isc in that part of the grid. Last but not least breakers and fuses are suggested for protecting the grid based on the results from Isc simulation.

6.4.1 Isc at point A, B and C

As we mentioned in the model description three fault points are tested.

- Point A - Short circuit at the battery
- Point B - Short circuit at transmission level
- Point C - Short circuit at distribution level

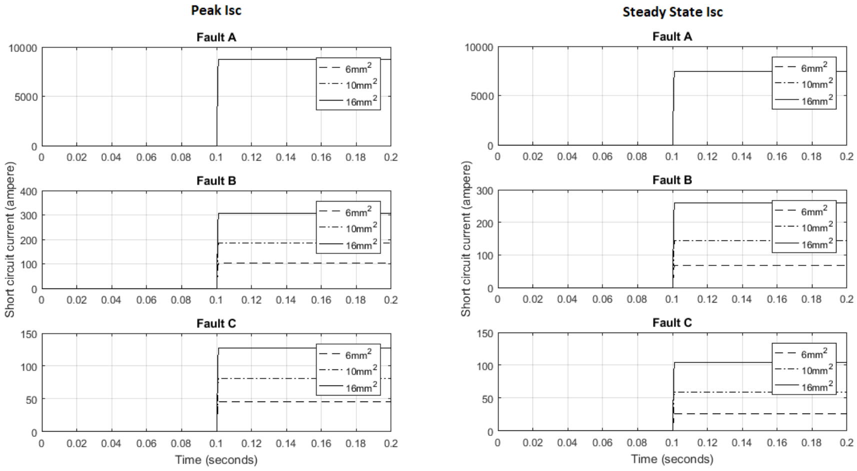


Figure 6.15: Short circuit currents in design A at Point A, B and C with $6mm^2, 10mm^2, 16mm^2$ cable. To the left peak short circuit currents and to the right steady steady short circuit currents

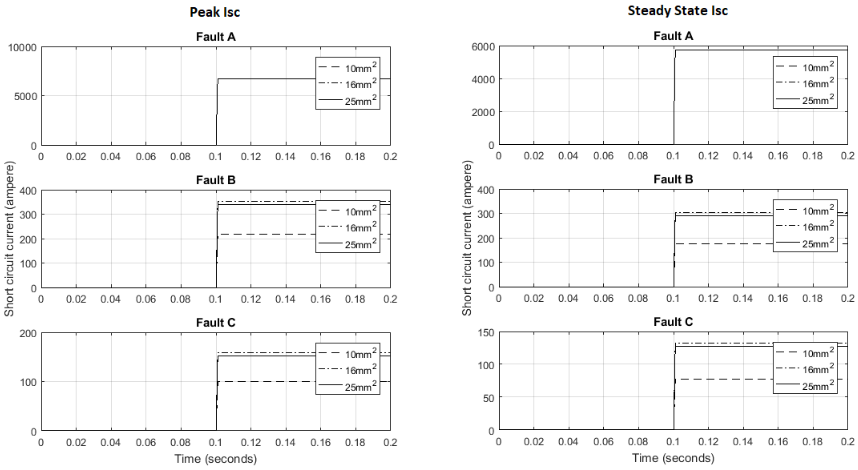


Figure 6.16: Short circuit current in Design B at Point A, B and C with $10mm^2, 16mm^2, 25mm^2$ cable. To the left peak short circuit currents and to the right steady steady short circuit currents

Table 6.1: Summary of short circuit currents at point A, B and C

Design A

Cable cross section (mm^2)	Short circuit current (Ampere)					
	Point A		Point B		Point C	
	ipb	ikb	ipb	ikb	ipb	ikb
6	8744	7444	103	67	46	27
10	8744	7444	185	145	80	60
16	8744	7444	306	259	127	103

Design B

Cable cross section (mm^2)	Short circuit current (Ampere)					
	Point A		Point B		Point C	
	ipb	ikb	ipb	ikb	ipb	ikb
10	6722	5714	216	174	100	77
16	6722	5714	353	302	158	132
25	6722	5714	338	289	152	127

6.4.2 Isc versus cable limit

To make sure that all cables can handle the maximum possible short circuit current, below is a table comparing the cable chosen to the peak short circuit current in that part of the system. The starting temperature is assumed to be around 50 degrees, to take into consideration that the grid is in a climate with a high average ambient temperature. The comparison is based on the table in figure B.2 from Nexans.

Table 6.2: Short circuit current compared to the cable Isc limit

Design A	Cable type	Cable cross section (mm^2)	Cable Material	Isc (Ampere)	Isc limit (Ampere)
Design A: $6mm^2$					
	Transmission Cable	6	Cu	103	744
	Distribution Cable	4	Cu	45	496
Design A: $10mm^2$					
	Transmission Cable	10	Cu	185	1240
	Distribution Cable	4	Cu	80	496
Design A: $16mm^2$					
	Transmission Cable	16	Cu	306	1980
	Distribution Cable	4	Cu	127	496

Design B	Cable type	Cable cross section (mm^2)	Cable Material	Isc (Ampere)	Isc limit (Ampere)
Design B: $10mm^2$					
	Transmission Cable	10	Cu	216	1240
	Distribution Cable	6	Cu	100	744
Design B: $16mm^2$					
	Transmission Cable	16	Cu	353	1980
	Distribution Cable	6	Cu	158	744
Design B: $25mm^2$					
	Transmission Cable	25	Al	338	2050
	Distribution Cable	6	Cu	152	744

6.4.3 Suggestion for grid protection

Using the above results from the short circuit current simulations, proper grid protection can now be suggested. For simplicity we will assume that each design has one breaker close to the batteries and then each house having a fuse.

For picking possible breakers in the system, the steps outlined in the document from ABB gives us that the three important factors are:

- Rated operational voltage Ue $\geq$ Line voltage Un
- ultimate short-circuit breaking capacity Icu $\geq$ Steady state short circuit current Ik
- Rated current of the trip unit In $\geq$ Rated current absorbed by the load Ib

Design A

For design A the line voltage Un is around 672V. The rated current In is in this case $In = 26 * 15A = 390A$. The steady state short circuit current Ik at the batteries is 7444A. Using the tables from the ABB document on breakers, a T5N16 breaker can be used for this design. It can have a maximum uninterrupted current of 400A and can break up to 16kA.

Moving on to fuses, as we will talk about in future work, no transient analysis have been done as a part of this thesis. This means that we lack data on the rise time of the short circuit currents in the system, and have not added fuses.

Design B

For design B the line voltage Un is around 720V. The rated current In is in this case $26 * 30A = 780A$. The steady state short circuit current Ik at the batteries is 6722A. Using the same tables as before a T6N16 breaker can be used for this design. It can break 16kA and an uninterrupted current of 800A.

6.5 Summary of simulations

Summarizing all the simulations we can start with a comment on the overview. Because both designs have the Homer residential profile as a base load profile, but scaled differently, the simulation results are naturally similar. The peak load for both A and B is about 2/3 of the maximum load the systems where designed for. Both designs also have the same solar radiation input in W/m^2, but different sized PV array. Non of the designs ever reach peak PV production in this simulation, but this of course depends on the irradiation profile. The batteries for both designs reach a peak SOC of around 80%. Thus both would be quickly fully charged if the load would be lower or starting at a higher state of charge. To alleviate this some sort of dump load would be needed. Examples of this could be other things needed on the Rutland, like a water desalination plant or similar.

For losses we see that for both design A and design B if using copper cables, a bigger cable cross-section gives lower total losses. The difference is generally higher when going from $6mm^2$ to $10mm^2$ in Design A and lower between the last two steps, $10mm^2$ to $16mm^2$. For design B with the switch to aluminium cable in $16mm^2$ to $25mm^2$, it gives slightly lower losses for the $16mm^2$ version. This is because Al has a higher resistivity per meter (0.0277Ω/m) than Cu (0.017Ω/m) and the increase in cross section does not do enough to alleviate that difference. When looking at the losses one has to take into account that the average load on the system is quite low compared to the maximum possible load. The maximum load reached is only around 11kW for design A, as we talked about in the overview. Looking at converters, you can conclude that they are a big part of the total losses and becomes an even bigger part as cable cross section increases (as the losses in those are reduced). But one has to have in mind that only the SSO on the PV array was based on a real actual efficiency curve. The 48V PV electronics used the built in average efficiency curves of Simescape and are not as accurate. So this result can vary if the actual real efficiency range of the 48V power electronics is better or worse.

Moving on to energy efficiency, which is linked to the above losses versus the amount of energy produced. The average efficiency of all systems is at worst 90%, which should be considered okay. But again one has to have in mind that the two designs even at the point with the highest load does not come close to the maximum load that Homer proposed. This becomes clear when looking at the point with maximum load in all the designs. Design A with $6mm^2$ 700V transmission cable being the worst at only 78% efficiency. With a higher load closer to the maximum what the grid is designed for, 17.8kW, this will become even worse and possibly go down to 50% efficiency.

Looking at short circuit currents we can see that a larger cross-section gives a higher Isc. This makes sense if comparing to the theory, a larger cable cross section gives a lower total resistance and thus a higher Isc from Ohms law, $Isc = Ue/Rtot$. Because of the length of the transmission line, in this case 1000m, it reduces the Isc after the cable and at distribution level to less then 1/10 of the short circuit current compared to the Isc at the batteries. Because we only took into account the resistive part of the system when simulating short circuit currents, and decided that the contribution from DC/DC converters was null this has to be investigated further. All the cables chosen as examples could also handle the Isc, but the tables used where written for AC transmission. Non the less, for the cables themselves it does not matter if it is AC or DC flowing through them as long as the current is not above current carrying capacity. The breakers and fuses proposed is included as a cost in the next chapter. Because we only used information from ABB and breakers from ABB it could be argued that they might be biased when it comes to selling their own equipment.

One last important aspect to mention in regards to calculating and simulating short circuit current is that it is debated whether IEC 61660-1 is accurate enough, with for example [32] proposing a more accurate method for meshed and complex networks. But for a grid of this size and radial topology we have stilled chosen to use it. ABB in their document also concludes that for a LVDC network up to 700V it is accurate enough.

Chapter 7

Cost analysis

In this chapter a cost analysis of the two designs and their variations have been done. The equipment cost have been gathered from the internet, from manufacturer themselves (through quotations) and from the pre-study.

The cost for solar PV is the lowest cost at the time of writing per installed Wp in India. This was because no response for a quotation was given by TATA power. But a general number gives a bigger freedom, being able to choose other Indian manufacturers which provide similar solar PV instead of just TATA. Many of the costs are also from Swedish, European or American websites which will have higher prices compared to if everything was bought in India. For calculations on a return of investment the payback method has been used in two different ways. First with a set electricity price, the price that a resident on Rutland is paying today (around 2 INR/kWh or 0.29 SEK/kWh). Then with a set system lifetime of 20 years, an normal life expectancy for example solar panels. Three components are also included taken directly from the pre-study: smart consumer meters, smart grid control middle layer system and smart grid meter and control top. They are all related to measuring and automating the system as much as possible.

The section called "other costs" which include installation cost, labour cost and so on, is directly taken from the pre-study and numbers provided by Teroc, as it was. This is simply to give an approximation of what range those numbers could be in. They are the same for all designs, even though a larger cross section of cable or more installed PV in theory should give a slightly higher cost, it being a bigger system overall and thus labour costs should go up.

7.1 Design A

The total costs of design A can be seen below. With all the different component and component types listed first followed by other costs as mentioned above. The important parts are bold for easier distinction.

Table 7.1: Economic analysis of design A

Component type	Component	Quantity	Cost €	Cost SEK	Total cost SEK		
Equipment costs					$6m^2$	$10mm^2$	$16mm^2$
PV modules	TATA Solar TP300W Panel	37000	0.288	2.81664	104215.7	104215.7	104215.68
PV Power electronics	Ferroamp Solar String Optimizer	10	2500	24450	244500	244500	244500
PV transmission cables	2x10mm^2 Cu cable	100	7.5	73.35	7335	7335	7335
Distribution cable	2x4mm^2 Cu cable	200	1	10	2000	2000	2000
350V/48V Power electronics	FEAS 720W 15A 400V/48VConverter	26	423	4136.94	107560.4	107560.4	107560.44
700V transmission cables	EKJJ 3x6mm^2 Cu cable	1000	-	50	50000	0	0
	EKJJ 3x10mm^2 Cu cable	1000	-	88	0	88000	0
	EKJJ 3x16mm^2 Cu cable	1000	-	130.5	0	0	130500
Breakers	T5N16 ABB Breaker	1		3700	3700	3700	3700
Battery storage system	Lead Acid Enersys 12V/109Ah	224	500	4890	1095360	1095360	1095360
Smart consumer meters	-	26	100	978	25428	25428	25428
Smart grid control middle layer system	-	1	-	50000	50000	50000	50000
Smart grid metering and control top	-	1	-	400000	400000	400000	400000
Total equipment cost					2090099	2128099	2170599.12
Other costs							
Supervision of installation	-				100000	100000	100000
Installation of PV modules	-				100000	100000	100000
Installation of PV Power electronics	-				50000	50000	50000
Installation of DC grid	-				100000	100000	100000
Installation of Smart consumer meters (26)	-				50000	50000	50000
Installation of Smart grid control middle layer system	-				50000	50000	50000
Configuration of system	-				200000	200000	200000
Installation of Battery storage system	-				100000	100000	100000
Project management	-				200000	200000	200000
Total other costs					950000	950000	950000
Total investment cost					**3040099**	**3078099**	**3120599.12**

7.1.1 Payback time

Below is the payback time for the three variations of design A. With Investment cost at the top taken from table 7.1. Followed by kWh produced by the PV panels, total losses in kWh and then the net energy output in kWh for each year.

Table 7.2: Payback time and cost per kWh of design A

Design A	$6mm^2$	$10mm^2$	$16mm^2$
Investment cost <SEK>	3040099	3078099.12	3120599.12
PV prod. <kWh/year>	81577.5	81577.5	81577.5
Losses <kWh/year>	7738	6522.55	5986
Total energy <kWh/year>	73839.5	75054.95	75591.5
Energy price <SEK/kWh>	0.29	0.29	0.29
Payback Time <years>	141.9714	141.418186	142.35313
System lifetime <years>	20	20	20
Energy price <SEK/kWh>	2.058586	2.0505637	2.06412038

7.2 Design B

The total costs of design B can be seen below. As with design A, all the different component and component types listed first followed by other costs.

Table 7.3: Economic analysis of design B

Component type	Component	Quantity	Cost €	Cost SEK	Total cost SEK		
Equipment cost					$10mm^2$	$16mm^2$	$25mm^2$
PV modules	TATA Solar TP300W Panel	86000	0.288	2.81664	242231.04	242231.04	242231.04
PV Power electronics	Ferroamp Solar String Optimizer	15	2500	24450	366750	366750	366750
PV transmission cables	2x35mm^2 Al cable	100	30	293.4	29340	29340	29340
Distribution cable	2x6mm^2 Cu cable	200	2.65	26	5200	5200	5200
350V/48V Power electronics	Scheafer Power C4589G 1440W 30A	26	1500	14670	381420	381420	381420
700V transmission cables	EKJJ 3x10mm^2 Cu cable	1000	-	88	88000	0	0
	EKJJ 3x16mm^2 Cu cable	1000	-	130.5	0	130500	0
	3x25mm^2 Al cable	1000	-	200	0	0	200000
Breaker and fuses	T6N16 ABB Breaker	1	0	7500	7500	7500	7500
Battery storage system	Lithium Ion SmartBattery 12V.8/150Ah	224	1899	18572.22	4160177.3	4160177.3	4160177.3
Smart consumer meters	-	26	100	978	25428	25428	25428
Smart grid control middle layer system	-	1	-	50000	50000	50000	50000
Smart grid metering and control top	-	1	-	400000	400000	400000	400000
Total equipment cost					5756046.3	5798546.3	5868046.3
Other costs							
Supervision of installation	-				100000	100000	100000
Installation of PV modules	-				100000	100000	100000
Installation of PV Power electronics	-				50000	50000	50000
Installation of DC grid	-				100000	100000	100000
Installation of Smart consumer meters (26)	-				50000	50000	50000
Installation of Smart grid control middle layer system	-				50000	50000	50000
Configuration of system	-				200000	200000	200000
Installation of Battery storage system	-				100000	100000	100000
Project management	-				200000	200000	200000
Total other costs					950000	950000	950000
Total investment cost					**6706046.3**	**6748546.3**	**6818046.3**

7.2.1 Payback time

Below is the payback time for the three variations of design B. With Investment cost at the top taken from table 7.3. Followed by kWh produced by the PV panels, total losses in kWh and then the net energy output in kWh for each year.

Table 7.4: Payback time and cost per kWh of design B

Design B	$10mm^2$	$16mm^2$	$25mm^2$
Investment cost <SEK>	6706046.3	6748546.32	6818046.32
PV prod. <kWh/year>	130195.5	130195.5	130195.5
Losses <kWh/year>	12410	9855	10037.5
Total energy <kWh/year>	117785.5	120340.5	120158
Energy price <SEK/kWh>	0.29	0.29	0.29
Payback Time <years>	196.3255	193.375043	195.663248
System lifetime <years>	20	20	20
Energy price <SEK/kWh>	2.8467198	2.80393813	2.8371171

7.3 Summary of costs

Summarizing the costs, we can start with Design A. About half the cost for all three variations is split equally between equipment cost and other costs. The difference between the three variations are quite small, only differentiating 80000 SEK between the smallest and the largest cross section in total costs. This can be contributed to the small size of the system, meaning it is possible to use short cables and relatively small cross sections, giving a low impact on cost. Cables per se, are also a small part of the total equipment cost. Thus changing cross section will not give a big impact on the total costs. Batteries, power electronic converters and smart metering control system dwarfs the cost of cables in a system of this size. We can also see that PV modules are very cheap, only costing 2.8 SEK per installed Wp. This is in line with what the trend has been in the last couple of years with prices of solar PV skydiving with increased demand and production in China, India and elsewhere.

Looking at the future scenario with a larger system in design B. Here the other costs are only about 1/6 of the total costs and equipment cost 5/6. But as mentioned in the cost analysis introduction, the "other costs" in design B should probably be slightly higher, it being a larger system. The same as in design A can also be noted here, the difference between the three variations in cable cross sections are very small compared to the total investment cost. If making a comparison to design A, we see that design B has a significantly higher battery cost even though the installed amount of kWh is almost the same, 280kWh in design A and 336kWh in design B. The main factor here being that the batteries is Lithium-ion based in design B. If comparing the price per Wh, we pay 3.91 SEK/Wh for Lead-acid and around 12.3 SEK/Wh for Lithium-ion. For comparison Teroc provided some quotations from manufacturers of Lithium-ion battery systems. O'Cell gives a price of 6,2 SEK/Wh and Tesla 4.2 SEK/Wh. Thus prices in reality are much lower if buying a complete battery system. We can see that in general the same rules apply to design B as design A, that converters and batteries are a big part of the cost, but seems to be getting an even bigger part of the total investment cost in the larger system. For the 48V DC/DC converters in design B which was from Schaefer power, they are three times more expensive then the converters in design A from FEAS. Even though the converters in B only has double the conversion power compared to A.

Moving on to payback time and cost per kWh. As previously stated, two ways was used to calculate this. Inputting a set energy price to get a payback time in number of years, and inputting a system lifetime to get a set cost per kWh. We can see that for Design A the one with smallest cable cross-section is the cheapest and has the shortest payback time. For Design B the one with medium cross section is the cheapest and has the shortest payback time. This can be related to the results from simulations of losses and efficiency. Where a larger cross-section gave lower losses. But combining it with these results it seems that the losses where not large enough to alleviate the increase in cable cross section. For design B the largest cross section, $25mm^2$, had lower losses then the medium sized $16mm^2$ version because of the higher resistivity in aluminium. But the payback time and cost/kWh are non the less almost the same for all variations of Design A and for all variations of design B respectively. This can be related to the above fact, cables are a quite small part of the total cost, giving a low impact on the total investment cost and thus on payback time. For both designs the first method, can seem to yield extremely high payback time, with on average 141 years for A and 193 years for Design B. But one has to have in mind that the price/kWh we used here (0.29 SEK/kWh) is the price that the population of Rutland is currently paying per kWh, and will most likely pay even after this grid is installed. It is unlikely and unrealistic to accept a payback time of 193 years, so the electricity price will have to be subsidized even in the future. When using a set lifetime of 20 years, the same number as used in the pre study, it looks more realistic. We can see that both our designs are actually cheaper then price suggested of 26-30 INR (3.3-3.8 SEK) per kWh, design A being around 50% cheaper and design B around 30% cheaper. Why this is should be discussed. But one factor is that the economic analysis in the pre study was not based on simulations of grid losses or real components, only estimations where used from Homer software simulations.

Chapter 8

Conclusion

Conclusion of this thesis. In the introduction we asked ourselves a few questions.

- How do you design a high quality, reliable DC microgrid with as low cost as possible?
  - Which components and factors are the most important when designing a DC microgrid?
- Which design with which components is most suitable for a grid on Rutland Island thinking both short term and long term?

Looking at our results, we can conclude that cables are an important aspect for a DC system when it comes to losses and efficiency. But with an increasing cable cross section and thus the losses being reduced there, power electronic DC/DC converters become a bigger factor for efficiency and losses in a system of this size. Overall when including the economic perspective (with payback time and cost/kWh), DC/DC converters and batteries are expensive and a bigger part of the cost than cables. This is confirmed with the dominating factor especially in design B, being the Lithium-ion based batteries. For safety aspects it is of vital important to get the right protection in the grid like fuses and breakers. Our short circuit currents where more than high enough to harm even at distribution level.

Which design is most suitable then. Evaluating from the parameters we set up: losses, efficiency, safety and costs. A higher cable size is required for both designs even though the payback time was lower for the smallest cable size. This is to take into account that the simulations never reached maximum load in either of the designs. The current design or the future design depends on factors like the future of Rutland as a community. The price per kWh for design B was of course more expensive because it was designed for a higher electrical consumption per house and used more components. When deciding you also have to understand and take into account future prospects. At the moment Lithium-ion batteries are very expensive and so are DC/DC converters. But with an increasing proliferation of DC, which seems to be unavoidable now that so much of power production and consumption is being geared in that direction. The prices for these should come down and design B could be a viable alternative. Design B also had a price per kWh, almost 30% less than the price in the pre study.

Looking at the thesis as a whole. For short circuit analysis and other possible transient problems a recommendation for further analysis of DC systems is to use a different software for this. Simulink simscape power systems is easy to use and has a lot of good finished components, but for looking at shorter time periods and more a more complex system, EMTDC is recommended by many sources.

8.1 Future work

Looking to next step after this thesis. The first and most urgent thing is to look at transient problems in DC grids. Which there was unfortunately no time to look at in this thesis. This is a critical part of a DC grid and could cause big problems if not addressed properly as was stated when interviewing Telia. This leads to what mentioned when dimensioning grid protection, which is that without a transient analysis its hard to pick the right fuses when you lack short circuit rise times. Another factor not looked at which is a fairly quick affair is to check the load factor in the grid on different cables. To get an easier approximation of cable dimensioning.

Other important work to look into is developing the models used further. For the steady state model this means more sources of renewable energy, automation and overall a more realistic model including proper efficiency curves for the 48V converters. It also means making the loads more realistic. Adding a random factor to each load which would add +/- 10% power, making for a more realistic scenario. Concerning loads, the fact that we never reached maximum load in our simulations, have to be addressed. Most likely by just scaling the load profile differently. Last but not losses in the batteries have to added. It is quite unrealistic to assume that no power is lost in the batteries, with the heat generated and so on. For the short circuit current model it means to include the Isc contribution from capacitances in the system and a more realistic battery model. The third and last thing to recommend is to look at other factors and parameters over the ones we did not include here, for example the environmental impact of a grid on Rutland Island and other factors like grid reliability.

For further work outside the mediate vicinity of this thesis is to look into what impact battery placement has. At the moment batteries are stored in a central location like our generator house. A comparison to look into placing batteries with each customer instead would be an interesting prospect. Would this be more efficient? What would the cost benefit be?

Another point which has been addressed in other papers, but not for this Rutland case is to do a comparison study with an equivalent AC grid. To see the losses, stability and cost differences between an AC grid and a DC grid on Rutland.

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Appendix A

List of Abbreviations

RISE - Research Institutes of Sweden
SEA - Swedish Energy Agency
MNRE - Indian Ministry of New and Renewable Energy
DC - Direct current
AC - Alternating current
LVDC - Low voltage direct current
HVDC - High voltage direct current
LVAC - low voltage alternating current
DG - Distributed Generation
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronics Engineers
EDA&N - Electricity department of Andaman and Nicobar Islands
PV - Photo-Voltaic CB - Circuit Breaker MCCB - Modulated Case Circuit Breaker IGBT - Insulated-gate bipolar transistor VSC - Voltage Source converter MPPT - Maximum Powerpoint tracker EKKJ - SSO - Solar String Optimizer SOC - State of Charge EMTDC - Electro Magnetic Transient Design and Control

Appendix B

Definitions and standards

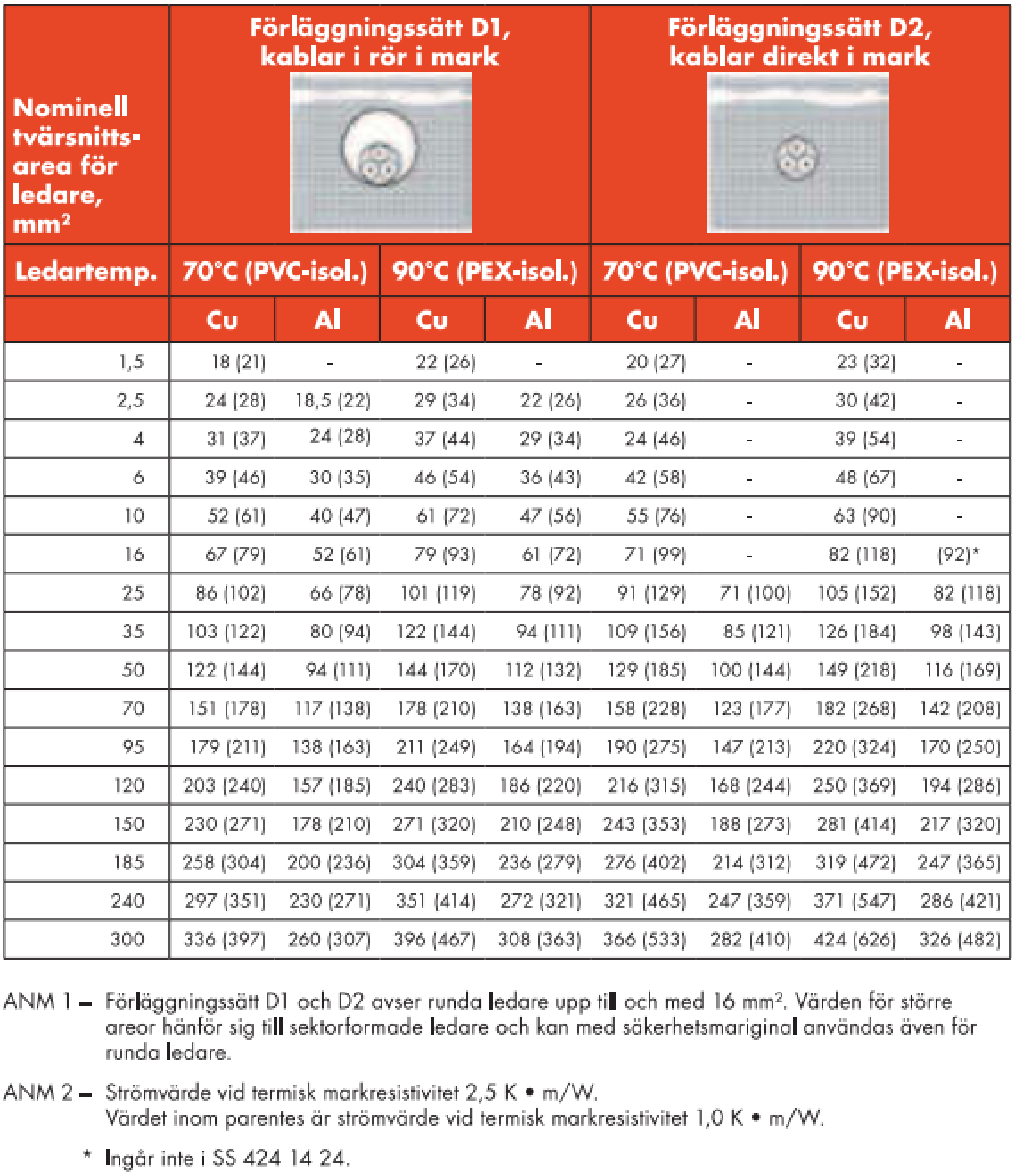
B.1 IEC 60038

The range of voltages defining high, low and extra low voltage for AC and DC.

IEC voltage range	AC (Vrms)	DC (V)	Defining risk
High voltage	>1000	>1500	Electrical arcing
Low voltage	50–1000	120–1500	Electrical shock
Extra-low voltage	<50	<120	Low risk

Table B.1: IEC 60038 - The standard voltage definitions from IEC

B.2 Swedish cable standards



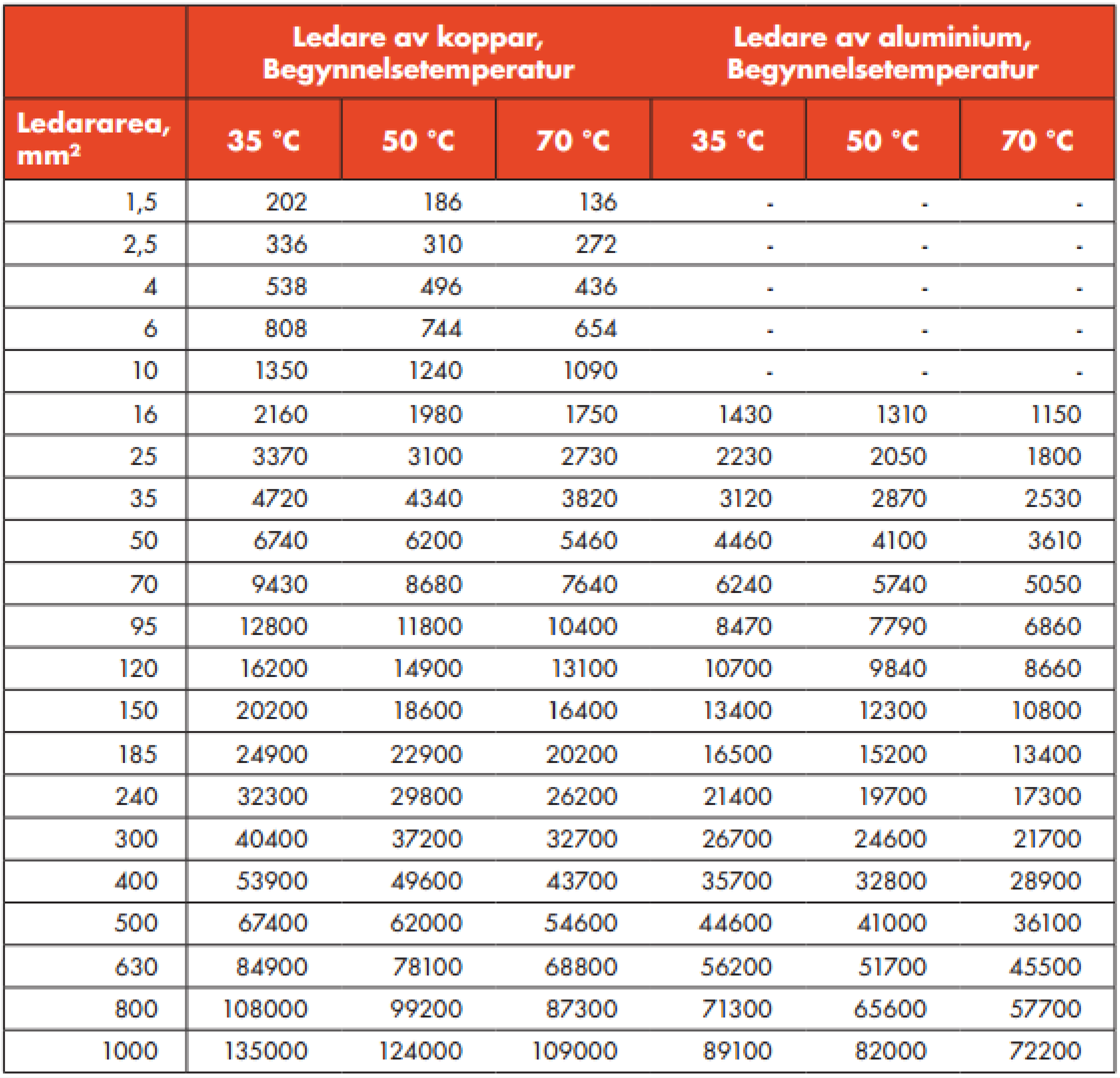
Nominell tvärsnitts-area för ledare, mm²	Förläggningssätt D1, kablar i rör i mark				Förläggningssätt D2, kablar direkt i mark			
Ledartemp.	70°C (PVC-isol.)		90°C (PEX-isol.)		70°C (PVC-isol.)		90°C (PEX-isol.)	
	Cu	Al	Cu	Al	Cu	Al	Cu	Al
1,5	18 (21)	-	22 (26)	-	20 (27)	-	23 (32)	-
2,5	24 (28)	18,5 (22)	29 (34)	22 (26)	26 (36)	-	30 (42)	-
4	31 (37)	24 (28)	37 (44)	29 (34)	24 (46)	-	39 (54)	-
6	39 (46)	30 (35)	46 (54)	36 (43)	42 (58)	-	48 (67)	-
10	52 (61)	40 (47)	61 (72)	47 (56)	55 (76)	-	63 (90)	-
16	67 (79)	52 (61)	79 (93)	61 (72)	71 (99)	-	82 (118)	(92)*
25	86 (102)	66 (78)	101 (119)	78 (92)	91 (129)	71 (100)	105 (152)	82 (118)
35	103 (122)	80 (94)	122 (144)	94 (111)	109 (156)	85 (121)	126 (184)	98 (143)
50	122 (144)	94 (111)	144 (170)	112 (132)	129 (185)	100 (144)	149 (218)	116 (169)
70	151 (178)	117 (138)	178 (210)	138 (163)	158 (228)	123 (177)	182 (268)	142 (208)
95	179 (211)	138 (163)	211 (249)	164 (194)	190 (275)	147 (213)	220 (324)	170 (250)
120	203 (240)	157 (185)	240 (283)	186 (220)	216 (315)	168 (244)	250 (369)	194 (286)
150	230 (271)	178 (210)	271 (320)	210 (248)	243 (353)	188 (273)	281 (414)	217 (320)
185	258 (304)	200 (236)	304 (359)	236 (279)	276 (402)	214 (312)	319 (472)	247 (365)
240	297 (351)	230 (271)	351 (414)	272 (321)	321 (465)	247 (359)	371 (547)	286 (421)
300	336 (397)	260 (307)	396 (467)	308 (363)	366 (533)	282 (410)	424 (626)	326 (482)

ANM 1 – Förläggningssätt D1 och D2 avser runda ledare upp till och med 16 mm². Värden för större areor hänför sig till sektorformade ledare och kan med säkerhetsmariginal användas även för runda ledare.

ANM 2 – Strömvärde vid termisk markresistivitet 2,5 K • m/W.
Värdet inom parentes är strömvärde vid termisk markresistivitet 1,0 K • m/W.

* Ingår inte i SS 424 14 24.

Figure B.1: Current carrying capacity according to SS424 14 24 for 0.6/1kV cable, source: Nexans Kabelboken [33]



	Ledare av koppar, Begynnelsetemperatur			Ledare av aluminium, Begynnelsetemperatur		
Ledararea, mm²	35 °C	50 °C	70 °C	35 °C	50 °C	70 °C
1,5	202	186	136	-	-	-
2,5	336	310	272	-	-	-
4	538	496	436	-	-	-
6	808	744	654	-	-	-
10	1350	1240	1090	-	-	-
16	2160	1980	1750	1430	1310	1150
25	3370	3100	2730	2230	2050	1800
35	4720	4340	3820	3120	2870	2530
50	6740	6200	5460	4460	4100	3610
70	9430	8680	7640	6240	5740	5050
95	12800	11800	10400	8470	7790	6860
120	16200	14900	13100	10700	9840	8660
150	20200	18600	16400	13400	12300	10800
185	24900	22900	20200	16500	15200	13400
240	32300	29800	26200	21400	19700	17300
300	40400	37200	32700	26700	24600	21700
400	53900	49600	43700	35700	32800	28900
500	67400	62000	54600	44600	41000	36100
630	84900	78100	68800	56200	51700	45500
800	108000	99200	87300	71300	65600	57700
1000	135000	124000	109000	89100	82000	72200

Figure B.2: Maximum allowed current during 1s in a PVC isolated copper and aluminium cable, source: Nexans Kabelboken [33]